Modern process visualization techniques in process data management systems

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ABSTRACT OF THE
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Tremendous advancements in sensors, communication networks, mobile devices and cloud-based technologies along with their decreasing prices have enabled the Industrial Internet of Things. The two major consequences observed are the exponential growth of collected process data in industrial processes and the need for visualizing it on mobile devices. These have created a demand for new, more efficient and more powerful techniques to gain value from the larger data sets that work seamlessly across multiple platforms.

One such technique is visualizing process data in three dimensional space which is implemented in this Master's thesis. 3D visualization was demonstrated to offer immense opportunities to industries by enhancing data interactivity and enabling the partitioning of process data into multiple layers. The biggest challenge in the implementation of this technique was obtaining 3D models of the manufacturing equipment, thus indicating the need to create and provide 3D models as a part of the package.

Keywords: Process data visualization, Industrial Internet of Things, 3D modeling

Preface

This Master's thesis was done during the time period 3.10.2016 - 11.5.2017 at the Process Industries CPM unit, which is a part of the Process Automation division at ABB Oy. The work was focused on improving ABB's process information management systems by integrating into them a 3D visualization component. Visualizing process data in three dimensional space enables more efficient visualization of the increasing amounts of gathered process data, resulting from the Industrial Internet of Things.

At first, I would like to thank my supervisor, Prof. Valeriy Vyatkin, and my instructor, M.Sc. Jukka Kostiainen, for their inexhaustible patience, excellent guidance and endless encouragement. I am also very grateful to the entire CPM unit for providing me with this unique opportunity and positive experience.

I would also like to express my deep gratitude to my dear family and friends for supporting me with the decisions I have made and for their love throughout my life. You fill my heart with warmth and joy, and give a meaning to everything I do. Completing this work would have been impossible without all of you!

Otaniemi, 11th of May 2017

Dimitar Boyadzhiev

Contents

Symbols and abbreviations

Abbreviations

API	Application Programming Interface
APM	Asset Performance Management
CBM	Condition-based Maintenance
CIA	Confidentiality-Integrity-Availability
CM	Corrective Maintenance
CPM	Collaborative Production Management
DCS	Distributed Control System
FPS	Frames per Second
GUI	Graphical User Interface
IIC	Industrial Internet Consortium
IIoT	Industrial Internet of Things
IoT	Internet of Things
IoTSP	Internet of Things, Services and People
IT	Information Technology
I/O	Input/Output
PDM	Predictive Maintenance
PIMS	Plant Information Management System
PLC	Programmable Logic Controller
PM	Preventive Maintenance
PoC	Proof of Concept
SDK	Software Development Kit
TBM	Time-based Maintenance
UI	User Interface
UX	User Experience
VPN	Virtual Private Network
WEC	World Economic Forum

1 Introduction

Tremendous advancements in sensor technology and the decrease in their prices have inevitably led to the exponential growth in the number of sensors being deployed in production lines. Subsequently, unprecedented amounts of process data is being gathered every day. In the past, the gathered data has been largely underused by manufacturers. Its main purpose has been to provide real-time monitoring of plant-floor operations and historical trending, detect faults and alarms, and determine the reasons for downtimes and failures. According to Manyika et al. (2015), however, these activities harness only one percent of the collected data. The need for deeper insights supplied by proper data analysis have led to the emergence of terms like "Big Data" analytics, made possible by improvements in data mining algorithms. Additionally, the developments in cloud-based technologies, such as cloud computing, and the declining costs of data storages have both led to the rapid decrease in the costs of storing and processing data in the cloud. All of these developments have made the Industrial Internet of Things (IIoT) feasible.

IIoT is a topic widely discussed in the past few years and for good reasons. It is considered to be the marking point for the next industrial revolution, and therefore a driver of the next economic boom. Furthermore, IIoT can help deal with some of the great challenges that the world faces today, including energy and resource efficiencies, as well as climate and demographic changes. In a report by General Electric (Evans & Annunziata 2012), IIoT is estimated to have a potential economic impact of as much as $15 trillion dollars by 2030, which is hardly something that can be overlooked by industries. The vast majority of organizations, however, struggle to comprehend the effects IIoT will have on their businesses (O'Halloran & Kvochko 2015). In fact, companies feel a sense of urgency to implement Industrial Internet solutions and feel at risk of losing momentum and market share if they are too slow to adopt data-driven strategies (*Industrial Internet Insights Report* 2014). Along with the large number of unprecedented opportunities that will be brought by this latest technological wave, an equally substantial number of new risks, challenges and threats will have to be faced by organizations, industries and societies.

In this thesis, the IIoT impact on process data visualization is researched and the following research question is addressed: "Is it feasible to integrate a 3D visualization component into ABB's process information management systems for more efficient process data visualization that can be commercially utilized?". Manyika et al. (2015) emphasize the importance of embracing a data-driven decision making approach in order to use the full potential of IIoT. The IIoT opens an entirely new realm for data visualization, as it consists of interconnected devices that are self-aware, predictive, reactive and social, and apart from sharing information about the processes themselves, also share information about the device's status. This availability of more useful data creates new opportunities and imposes new challenges on data visualization techniques, whose central goal is to present the data in a humanly understandable way in order to aid the decision making process.

1.1 Purpose

This thesis has several purposes that are closely related to each other. First of all, it aims to uncover the impacts of IIoT on process data visualization and to suggest methods for coping with these impacts. Additionally, it aims to provide a methodology for selecting and evaluating two 3D visualization toolkits that are going to be integrated into ABB's PIMS solutions. The toolkits will be integrated using the suggested methods and will enable process data visualization in a three dimensional model of a manufacturing machine. The integration should be implemented in both a traditional desktop-based user interface as well as in platform-independent web-based user interface. Upon a successful integration, a small Proof of Concept (PoC) will be created using data from an ABB customer that will act as the basis for potential future development in which process data from entire manufacturing facilities can be represented in this manner.

1.2 Scope

In order to meet these goals, the thesis discusses the current trends in technology and how manufacturing industries are being affected by the latest one of them, the Industrial Internet of Things, which is considered to be the next industrial revolution. The literature review is presented in Section 2, which lays the basis of the thesis. It is divided into multiple sections starting with a brief description of process information management systems (PIMS) in Section 2.1 and the current situation in the manufacturing industry in terms of data collection and visualization in Section 2.2. The reader is then presented with the *Industrial Internet of Things* concept in Section 2.3, in which key themes, such as related concepts, the IIoT vision and its enablers, and the opportunities, challenges and risks faced by industrial companies are discussed. Following these, the central topic of the thesis — process data visualization — is presented in Section 2.4. The section discusses the importance of process data visualization for informative decision making, methods and techniques for improving visual representations of data, and the new restrictions and challenges imposed on process data visualization by the IIoT.

The implementation part of the thesis starts in Section 3, in which an implementation methodology is created and applied for finding and evaluating the two most promising 3D visualization toolkits available on the market, as well as for evaluating the market maturity. Section 4 discusses the integration of the two selected tools onto ABB's PIMS solutions and presents the results. Lastly, the thesis is concluded in Section 5 by discussing the made observations and discoveries, and by describing the vision and future improvements of the developed concept.

2 Literature Survey

The purpose of this section is to provide the reader with some background information about the latest trends in automation in the manufacturing industry. In order to achieve this goal, it is divided into several sections. Section 2.1 provides the reader with the basic idea of process information management systems. Following this is Section 2.2, which presents the current situation in industrial plants in terms of process data collection and visualization. Section 2.3 establishes a connection between the traditional practices of handling and exploiting data in manufacturing industries and the IIoT practices. It describes the IIoT vision and enabling factors; the opportunities, challenges and risks imposed by the IIoT, as well as several of the most important applications of IIoT. The last part of the literature review, Section 2.4, is dedicated to process data visualization. It presents the importance of process data visualization for insightful decision making, the essential role of the human visual system in designing visual displays, as well as the impact of IIoT on process data visualization.

2.1 Process Information Management Systems (PIMS)

Many industrial plants nowadays are equipped with process data storages, known as Process Information Management Systems (PIMS). PIMS are software solutions that collect real-time data from sensors inside manufacturing facilities, store the data in historian databases and then display it to the user upon request. Algorithms are run on the stored data to organize it and to yield extensive reports. The reports are presented to decision makers in order to provide them with real-time information about the performance of different processes in the manufacturing facility. This enables decision makers to make informed and cost-effective decisions. Other ways of presenting the analyzed data to decision makers are through process charts, dashboards and trend views. (Prevas 2017) As an example, the ABB PIMS desktop solution is presented in Figure 1. The trends shown in the figure are representations of two of the CPU cores of the computer running the application and are updated in real-time.

PIMS provide three key benefits, which are discussed below. (dataPARC 2015)

1. Better-organized production data

PIMS solutions enable proper organization of production data. This is because PIMS make possible the collection of data from various data sources located across the entire plant, which are also typically from different vendors. After the collection, the information system conditions the data and then archives it. The conditioning of data refer to methods, such as filtering, averaging, correlating time stamps and aggregating raw data, that are applied to the data. The conditioned data is presented to various decision makers throughout the production plant.(dataPARC 2015)

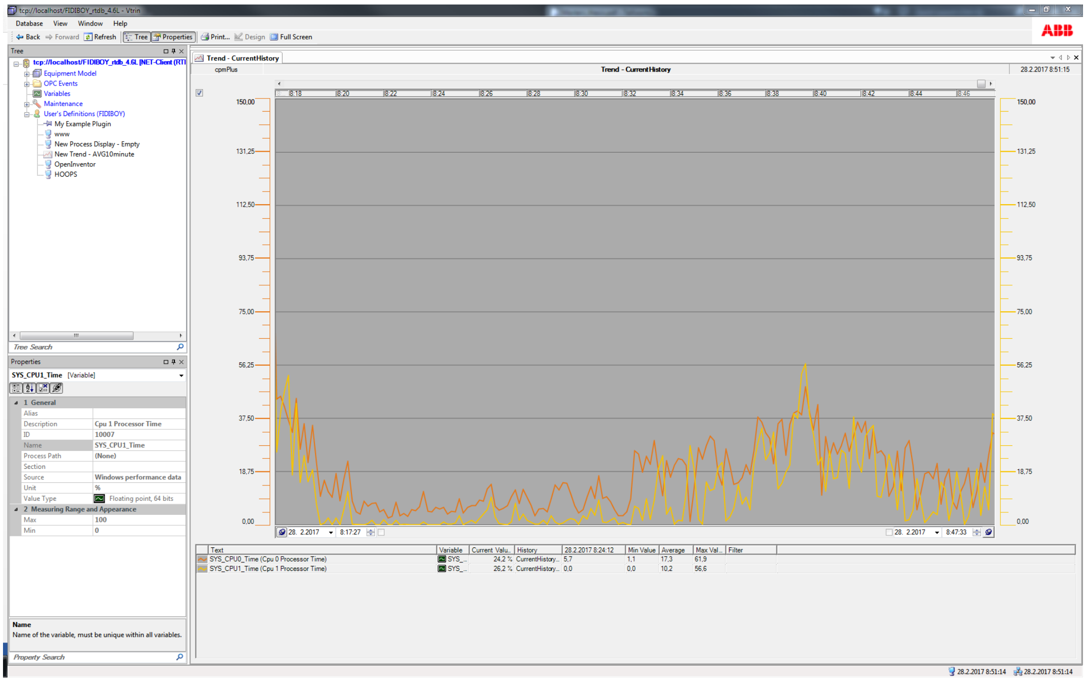


Figure 1: ABB PIMS showing two trends in the same graph makes it easier to compare trends and find patterns.

2. More efficient troubleshooting of quality problems

The trends which are visualized in PIMS solutions enable more efficient troubleshooting of problems. Placing graphs above each other or placing plots in the same graph allows to visually compare different measurements at specific time intervals. Thus, changes in one process variable can be easily associated with changes in another process variable, determining cause and effect.(dataPARC 2015) This can be seen in Figure 1.

3. Understanding real-time return on investment

Typically in manufacturing facilities expenses, such as electrical, fuel and raw material costs, are quite dynamic and the ability to monitor them is a crucial functionality of a PIMS solution. For example, generally manufacturing facilities both consume electricity from the grid as well as sell it back to the grid depending on the production rate and the price of electricity. Therefore, presenting an accurate, real-time information of the cost data can be used by engineers and operators across the plant to optimize efficiency and maximize profits. (dataPARC 2015)

According to ABB (2017), ABB's PIMS solution offers the following functionalities:

- The purpose is to collect and integrate production process data from different sources

- Collecting, archiving and consolidating data from production facilities, control systems and commercial systems.
- Conducting remote diagnostics on numerous plant components.
- Making data available to other evaluating applications (e.g. performance calculation, reporting)
- Delivering process parameters, status variables and counter readings to maintenance and financial systems.

2.2 Current situation in the manufacturing industry in terms of data collection and visualization

Traditionally, the main goal of manufacturers has been to produce products of satisfactory quality with low manufacturing costs. To meet this goal, sensors located around production plants collect specific sets of data which are typically transmitted via Input/Output (IO) cards into programmable logic controllers (PLCs) or distributed control systems (DCSs). (Prakash 2016) Though the amount of data gathered is huge, a very small portion of it is used - McKinsey (Manyika et al. 2015) estimates it to be under one percent of the globally collected data.

The most common use of the data is for alarms due to failures and for remote real-time supervision. A good example of this is a factory's control room in which the states of the systems are monitored in real-time. In case of a deviation or an anomaly, the operators in the control room are visually notified through the UI. Based on the notification they have to make a decision, for example to manually open or close a valve.

In many places measurements of physical quantities, such as the temperature, pressure, RPM and performance of machines, are collected and stored in the machine's own log until the buffer is full. Sometimes the data is stored in a local storage unit and sometimes it is simply overwritten by new data. Rarely, the data may be archived and, only in cases of a malfunction, used later for investigation purposes: for example to determine and understand the reasons a device has failed. Therefore, most data currently has a momentary meaning focused on the present moment. The data is typically used for monitoring the plant operations but not for other purposes that can bring much higher value to companies, such as product optimization and predictive maintenance, which are discussed in Section 2.3.7. (Collin & Saarelainen 2016, p. 48)

For the purpose of verifying this information from a real-life perspective, a production facility was visited and the current usage of data was investigated. The name of the facility is not mentioned in here due to privacy concerns.

Facility visit

The visited facility is in the metal manufacturing industry and is responsible for the production of metal disks. The only type of data collected by the facility is on the states of its systems. Each system could be in one of the following three distinguishable states:

1. Operational
2. Productional disturbance
3. Schedule maintenance

Based on this information, the total operational hours for each system are continuously calculated. In accordance to manufacturers' suggestions, each system is scheduled a maintenance check and maintenance work at certain intervals of operational hours.

The facility does not have a control room where operations are monitored at all times, nor are there any types of alarms in cases of malfunction. The facility does, however, have a process information management system (PIMS) in use for the purpose of visualizing the states of each system. The information is presented on TV screens placed at key locations around the production floor, and it is also accessible from the laptops of workers. In cases of malfunctions, systems are preprogrammed to automatically stop operating and wait for a person to solve the issue. As discussed with the workers in the factory, however, it is typical for malfunctions to go unnoticed for, sometimes, rather long periods of time due to the lack of a specifically assigned control room and alarms. Furthermore, the reasons for malfunctions are not displayed in the PIMS and therefore, after a problem is noticed the person needs to go to the physical location of the system and determine the issue from its main computer. Additionally, there are no logs of the reasons behind production disturbances nor what was done to solve the problems. Since there are three shifts of different workers per day, workers coming to one shift will be able to see what the states of a system were in the previous two shifts but will have no idea of the reasons behind disturbances nor the actions taken to solve them. Therefore, patterns of repeatedly occuring issues will easily go unspotted and will not be properly solved. The collected data is stored inside the facility with the possibility of remotely accessing it only if a VPN connection is opened from within the local network of the facility.

Even though there are facilities that collect data in the way mentioned in the beginning of this section for the purpose of real-time monitoring of processes, there are also cases in which very little amount of data is collected, as seen from the visited production facility. Therefore, it can be concluded that the hidden potential of data is majorly underused and possibly not even understood by some industries.

As argued by Vyatkin (2016) the focus of manufacturing has been lately shifting from the traditional focus of mass production with satisfactory quality and low manufacturing costs towards increased flexibility and customizability, while preserving the cost efficiency. Achieving this on large scales will be enabled by the so called Industrial Internet of Things, which is discussed in detail in Section 2.3.

2.3 The Industrial Internet of Things (IIoT)

New technologies have pushed industries forwards for centuries and have transformed ordinary people's lives in unimaginable ways. Revolutionary technologies have marked the beginnings of new eras and have led to economic booms (Figure 2). The first industrial revolution was marked by the invention of the steam engine and its use as a power source for mechanical production equipment. The second industrial revolution was marked by the invention of electricity and the era of mass production. The third, building on top of the second, was marked by the invention of Information Technology (IT) and electronics that were used to automate manufacturing processes and bring new levels of production and efficiency. Now, humanity is at the threshold of a fourth industrial revolution which, based on the fusion of existing technologies, is set to remove the boundaries between the physical and the digital world. This event is once again expected to disrupt industries and revolutionize the way people work and think, except that this time around it is expected to evolve at an exponential rather than a linear pace. (Schwab 2016)

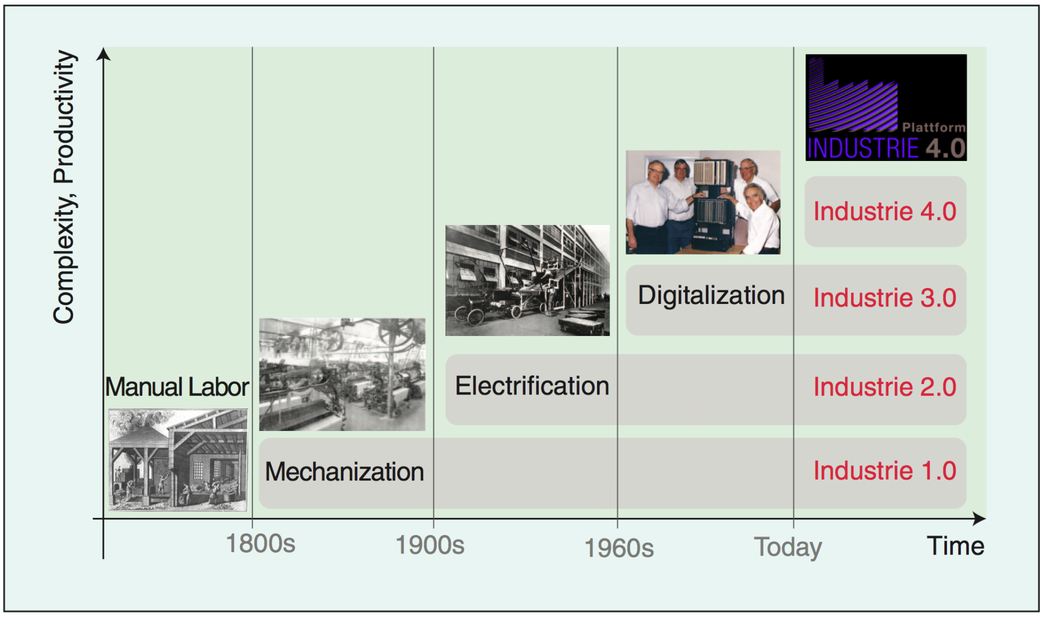


Figure 2: Four industrial revolutions. (Drath & Horch 2014)

As a starting point, Section 2.3.1 covers the related terminology.

2.3.1 Related Terminology

Three major terms are widely discussed when it comes to the connection between the physical and digital worlds: cyber-physical systems, internet of things, and the industrial internet of things. The central idea behind all of these three is the interaction and data exchange of physical objects connected to each other via a network.

Cyber-physical system(s) (CPS) is a term which was first used in the United States and is the oldest of the three. It is used to describe a generation of embedded systems, which by harnessing the Internet of Things technology, would lead to autonomous systems connected to a network that enables them to communicate with each other, with their constituent systems, as well as with people. Some examples of cyber-physical systems are Smart Grids, Smart Factories and Smart Buildings. (Collin & Saarelainen 2016, p.33) According to Sadeghi, Wachsmann & Waidner (2015), cyber-physical systems are the foundation of the industrial internet of things.

The Internet of Things (IoT) is defined as "a self-configuring and adaptive system consisting of networks of sensors and smart objects whose purpose is to interconnect all things, including everyday and industrial objects, in such a way as to make them intelligent, programmable, and more capable of interacting with humans." (IEEE n.d.) Described by IIC as the equivalent of a horizontal technology, IoT is centered around the consumers' world. (Kelley, Westcott & Quiring 2015)

The Industrial Internet of Things (IIoT), though in many ways similar to CPS and IoT, has its differences. According to Sadeghi & Wachsmann (2015), cyber-physical systems lay the foundation for the IIoT which brings the needed infrastructure to push the CPS concept forwards and to take intelligence to a new level by using modern technologies, such as cloud computing and Big Data analytics. Drath & Horch (2014) point out that IIoT is "often understood as the application of the generic concept of cyberphysical systems". Comparing IoT to IIoT, there are a few structured relationships between the two concepts. The Industrial Internet of Things, sometimes referred to as just the "Industrial Internet", is a specific branch of the IoT applied specifically to industrial environments. Also, IIoT is the equivalent of a vertical industry contrary to IoT, which is equivalent to horizontal technology. (Kelley & Westcott 2015) *Industry 4.0* is yet another term similar to IIoT, which originates in Germany, and is commonly used in Europe to outline that it is considered by to be the fourth industrial revolution. Be it the *Industrial Internet*, the *Industrial Internet of Things* or *Industry 4.0* — all of them are established on the same core principle lead by digitization.

2.3.2 Filling the gap between Information Technology and Operational Technology

The Industrial Internet Consortium (IIC) defines IIoT as the "internet of things, machines, computers and people, enabling intelligent industrial operations using advanced data analytics for transformational business outcomes." (Lin et al. 2015) As for the key role, according to another report issued by the IIC (Schrecker et al. 2016), "an Industrial Internet of Things (IIoT) system connects and integrates industrial control systems with enterprise systems, business processes and analytics." An essential takeaway is that IIoT solutions attempt to remove the solid boundaries within enterprises that have limited for decades the free movement of information and prevented making insightful decisions in real-time.

Collin & Saarelainen (2016, p. 48) emphasize that the underlying difference between the traditional industrial automation systems and the industrial internet lies in their relation to data. As emphasized in Section 2.2, in traditional automation systems data has had only a momentary meaning and was used for basic monitoring tasks. IIoT enables a whole new approach as everything is data-driven. Data is the raw substance, which has little value in its original form. After proper analysis, however, it yields information. This information can then be further refined to provide valuable knowledge, which can be either presented to humans or used directly by machines for the purpose of making insightful decisions. (Mazza 2009, p.8) According to Accenture's Technology Vision 2016, for companies to be fully data-driven they need to have more than better tools and better skills. Data would need to be used at every level in the company for decision making, not only by people but also by machines. (Morrish et al. 2016) The report outlines that one of the main differences between IIoT systems and traditional industrial control systems is that the IIoT systems are "connected extensively to other systems and people", making them broader and more diverse. This is achieved through the convergence and integration of Information Technology (IT) systems and Operational Technology (OT) systems, as shown in Figure 3.

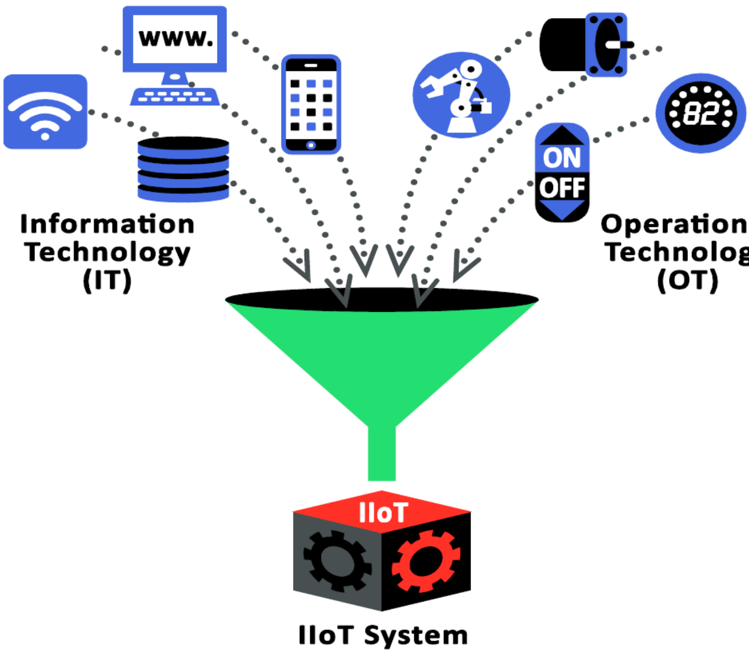


Figure 3: The convergence of IT and OT yields IIoT. (Schrecker et al. 2016)

In the past, IT and OT have been widely separated, as illustrated in Figure 4. IT has been responsible for the management of computers and the communications across industries. It has been used by businesses to improve agility, security and speed, reduce costs and provide business insights (Morrish et al. 2016). The software applications created have been used by people, with the risks being low and having no direct physical impact. The real-time requirements of IT systems have been generally quite soft, since they have typically been bound by human interaction times, and not meeting real-time deadlines have merely lead to inconvenient situations for people. (Schrecker et al. 2016) Furthermore, the triad of Confidentiality-Integrity-Availability (CIA) has been for a long period of time the approach to handling information in IT environments, meaning that the greatest weight has been to keep the information confidential, whilst availability has had the least importance (Rasekh et al. 2016).

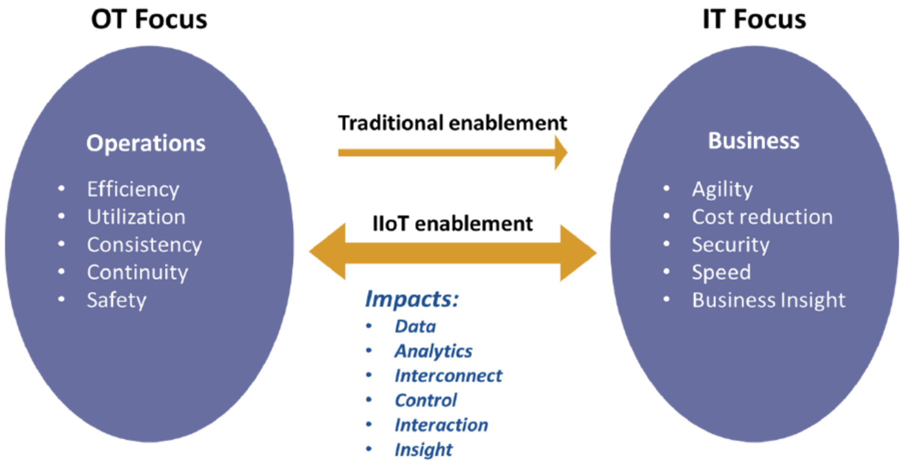


Figure 4: Current IT and OT focus and the existing gap between them. (Schrecker et al. 2016)

OT, on the other hand, has been responsible for the interaction between the physical world and the digital world and therefore, has consisted of both hardware and software. Data gathered from these has been generally used for the direct monitoring of plant operations and the control of automation systems. The set of requirements on OT systems has been quite the opposite to IT systems since physical changes occur that have the potential to cause hazardous situations for people's safety. The acronym AIC (Availability-Integrity-Confidentiality) has been used to describe the manner in which data is handled and to emphasize the importance of operations being fully functional (Rasekh et al. 2016). The key focus of OT has been to improve operational metrics, such as efficiency, utilization, consistency, continuity and safety (Morrish et al. 2016). Therefore, operations in OT have been customized and automated to handle specific tasks, and have required less human interaction. Due to the communications happening mainly between machines, the real-time requirements have been much stricter and the deadlines have been either firm or hard. Failures to meet these deadlines have had a significant impact on the correctness, reliability and safety of operations. As a result, the data security requirements of OT systems have been quite different, as they can directly affect safety.(Schrecker et al. 2016)

Traditionally, even though manufacturing industries have had industrial systems consisting of both IT and OT units for the purpose of controlling devices by software, they have only partially been integrated (if at all) and have typically been isolated on the OT side. As operations have been the core of everything, OT functions have acted as the enabler for IT functions. IIoT aims to change these by combining the expertise of IT, that has systems spread across many organizations and organizational levels, with the expertise of OT, that controls physical processes using sensors and actuators. This will involve the "merge of their key system characteristics", as illustrated by Figure 5, and will result in huge new implications and opportunities for individuals, organizations and societies. However, since the key system characteristics and their assurance have different priorities in IT and OT systems, the merge will also introduce new challenges, threats and risks (covered in Section 2.3.6) and a balance point will need to be found.(Schrecker et al. 2016, Morrish et al. 2016) As illustrated by Figure 4, IIoT will make the aforementioned enablement bi-directional and will have an impact on the data itself and data analytics, the interconnection and control of devices and the interaction between devices and humans. Furthermore, it will enable significant advances in optimizing the decision making process by providing new business insights and sharing valuable data across all levels within an organization.

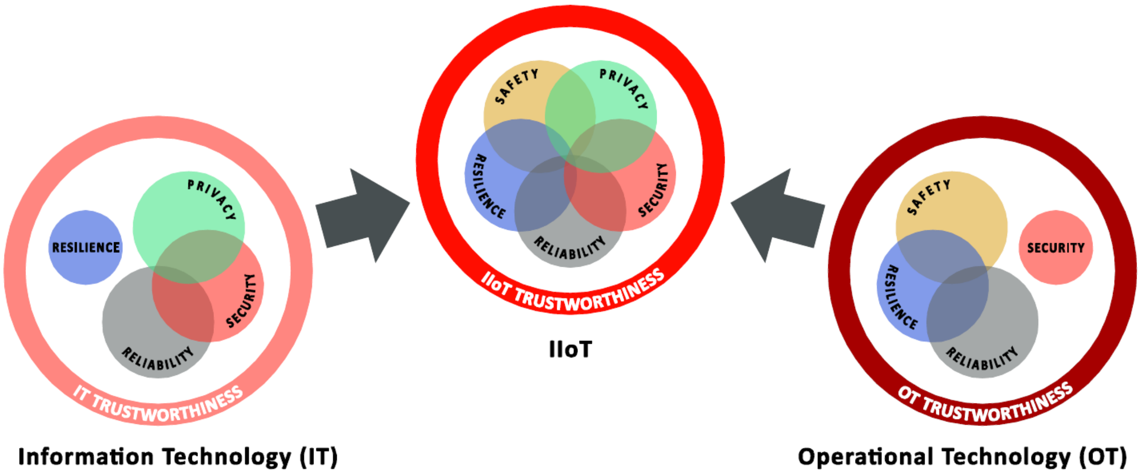


Figure 5: IIoT combines the key characteristics of IT and OT. (Schrecker et al. 2016)

2.3.3 IIoT vision

Intelligent data obtained from smart devices, delivered whenever and to whomever needs it for the purpose of making insightful decisions, is at the heart of the Industrial IoT vision. This is achieved via the omnipresent connection of machines, things and people enabling the production of a diversity of new products and services.(Collin & Saarelainen 2016, Koch et al. 2015) One way to think of IIoT is as a revolutionary way of handling data in industrial environments, made possible by evolutionary changes in different fields. Some of these fields are cloud computing, Big Data analytics, machine learning, sensor technology, communication infrastructure, device intelligence etc. The flow of data according to this vision is presented in Figure 6.

The key drivers of IIoT are the exponential growth of gathered raw data, the rapid increase in computing power, ubiquitous connectivity between devices and people, data analytic techniques. These are discussed in more detail in Section 2.3.4.

2.3.4 IIoT drivers

Every time a big change occurs, people tend to ask themselves questions, such as "Why did the change occur now?" and "What were the causes for the change?". These

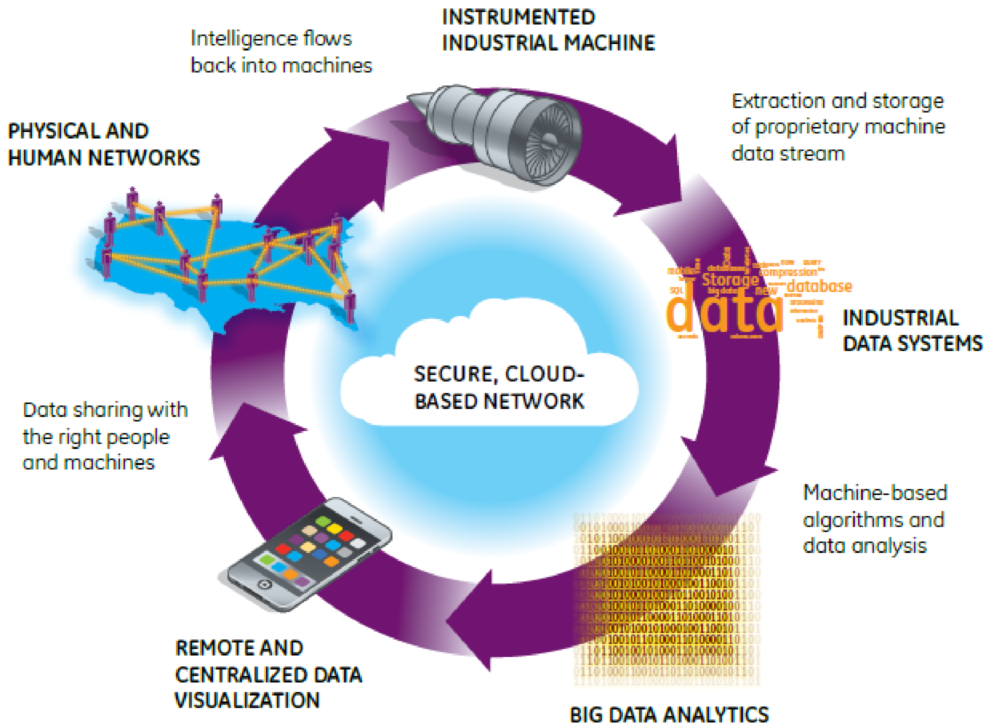


Figure 6: Data loop in IIoT. (Evans & Annunziata 2012)

type of questions are important to be answered so that businesses can learn from them and be able to predict future changes, which is vital for their success. With the industrial internet of things, being a major industrial revolution with impacts that will affect every industry, it is even more important to understand the answers to these questions, and therefore, this is the aim of this section.

The first thing that is crucial to realize is that it was not a single technology or idea that enables the adoption of the IIoT concept, but rather a number of different drivers that contribute to this process. Improvements in technology alone, though greatly contributing, are not enough. There are other aspects that are just as important, such as price, market readiness and technology maturity. Therefore, it is fair to say that there exists a point in time where the readiness of all these factors meet and that is the point when the widespread adoption of technology begins. According to an executive summary by the IIC, it was not until very recently that advancements in technology, communication networks and equipment reached that point both price-wise and performance-wise (*Industrial Internet Consortium: Introductory White paper* n.d.).

From the technology perspective, it was the improvement of old technologies and the creation of new ones that contributed to this shift. According to Gorbach, Polsonetti & Chatha (2014), the architecture of IIoT is based on existing and emerging technologies, such as "mobile and intelligent devices, wired and wireless networks, cloud computing, Big Data, analytics, and visualisation tools."

Sensor technology and communications

A very essential enabler of the IIoT is the consistent improvements in sensor technologies. In the recent years, sensors have continuously decreased in size, driven by the need for them to fit in smaller spaces, typically dictated by consumer electronic devices. The huge investments into sensor development have yielded innovative new methods and the use of new materials for their creation. A continuous perfection of microprocessor chips has increased sensor performance while energy consumptions have decreased dramatically, allowing them to operate for weeks on a single charge. Most importantly of all, however, the production costs of sensors have been greatly reduced leading to lower market prices and making them easily affordable. On the other hand, improvements in communication networks, both wired and wireless, have made it possible for sensors to transfer forward their acquired data more easily. As a result, the usage of sensors for different devices, located in different locations and environments, has been growing exponentially, making devices and systems increasingly intelligent. This has led to enormous amounts of data being collected from all kinds of devices. (O'Halloran & Kvochko 2015) Furthermore, these devices are increasingly connected to each other and to people, creating an intelligent network with seamless data transfer.

Cloud systems

One of the major enablers of IIoT, which can be also considered as a benefit, is cloud systems. The rapid decline in the cost of sensor production has been matched by the advancements in the field of cloud computing. In addition to being able to cheaply acquire the data, this has also made it a viable solution to cheaply manage, store and process large amounts of data in the cloud, instead of on local servers and computers, as has been previously the practice. (Schrecker et al. 2016, Evans & Annunziata 2012, Soley & Hoske 2015) This allows users of cloud services to be more flexible by being able to easily adjust the storage room and computing power as dictated by their needs. Users are also spared the trouble of maintenance because all the service related issues are handled by the cloud-services' provider. Furthermore, clients are also guaranteed the availability of their data at all times since it is typically backed up and stored across multiple locations and the risks of losing the data due to for example a natural disaster are minimal. Storing the data in the cloud also allows the data to be accessed from anywhere on any authorized device which can have enormous implications for users but also opens new security risks.

Big Data analytics

The increasing amount of acquired data coming from intelligent devices has created the need of new ways to process this data to give meaningful results. This has led to the development of new data analytic techniques that, apart from having to work on large amounts of data, also need to operate on myriad of different data types coming from different data sources and with different velocities (Elgendy &

Elragal 2014). These new data analytic techniques have been given the name Big Data analytics, whose purpose is to fulfil the new set of requirements and to examine such data in order to "uncover hidden patterns, correlations and other insights" in real-time. (SAS n.d.)

Mobile devices

The mobile device revolution has placed intelligent devices into every person's hands. These devices have accelerated the cost deflation of smart components and their miniaturization and have more importantly created an entirely new domain for software development and the affordable and efficient transfer of information across devices. Mobile devices are enabling operators to remotely monitor and control automation systems from anywhere and to present to them the intelligent data coming from data analytics, in order to help them make insightful decisions. (Evans & Annunziata 2012) The emergence of wearable technologies, such as smart glasses, and the development of virtual and augmented realities will further engage workers in their jobs and help them make the right decisions. (Conway 2015)

As the digital infrastructure advances, organizations will collect increasingly more data from their business processes. Adopters of IIoT will experience several phases after adoption that will bring along a number of opportunities for businesses on all levels. These phases and opportunities are discussed in the next section.

2.3.5 Phases and opportunities of IIoT

The Industrial IoT offers huge opportunities to adopters. As emphasized by Conway (2015), IIoT is not about replacing the current automation systems with new ones as many people think but rather about connecting them to other systems at different enterprise levels, such as planning, scheduling and product life cycle systems, through the use of the Internet. The World Economic Forum (WEC) outlines in a report (O'Halloran & Kvochko 2015) that the foundation for all advantages of the industrial internet of things is laid by the collection of massive volumes of data from the interconnected devices. Apart from lower storage costs, storing the process data in the cloud means that real-time data can be accessed on any device connected to the Internet from anywhere. The real value comes from the ability to filter out the valuable information from this data using sophisticated Big Data algorithms and with the help of advanced process visualization tools to use these insights to make intelligent decisions in real-time at any level in the company. These have huge implications for both customers and suppliers. O'Halloran & Kvochko (2015) claim that the evolution of the IIoT will follow four distinct phases, presented in Figure 7, with each one bringing new opportunities to adopters.

Businesses continuously explore new ways of differentiating themselves from their competitors and providing better customer experiences, and IIoT can help them with that. According to the WEC report, the first two phases after IIoT adoption are part of the short-term, immediate opportunities that adopting companies will

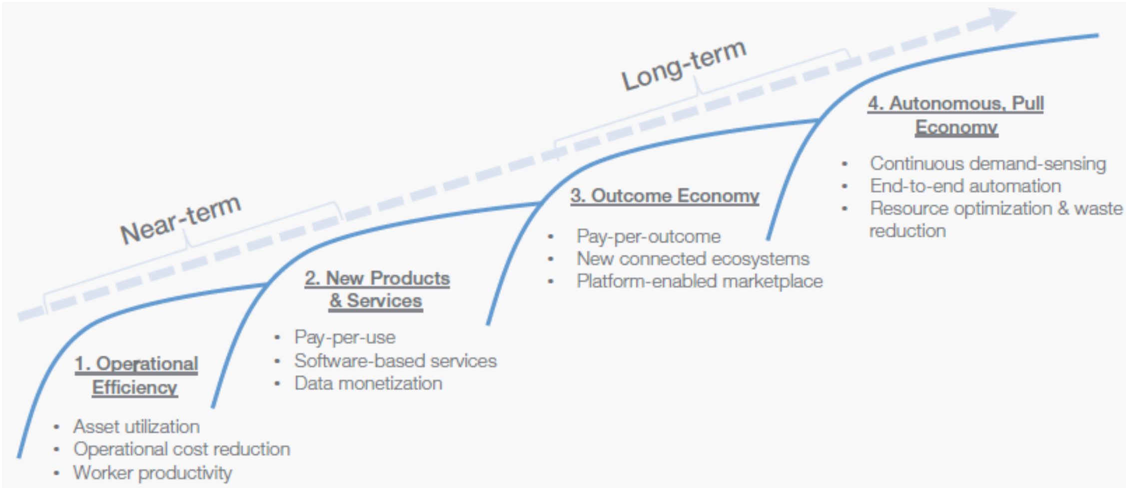


Figure 7: The four phases of the Industrial Internet. (O'Halloran & Kvochko 2015)

experience. O'Halloran & Kvochko (2015) claim that these also play an important role to drive businesses to adopt IIoT solutions, as they will bring incremental increase in revenues and cost savings. Koch et al. (2015) emphasize that organizations can increase their efficiencies by as much as 18% within the first five years after IIoT adoption. As will be later discussed in Section 2.3.7, predictive maintenance and remote asset management are some of the first and most direct applications of IIoT. Both of these will result in significant cost-reductions by eliminating waste. Using the gathered operational data suppliers can anticipate equipment failures and thus reduce unexpected downtimes and critical situations, such as leaks, fires etc. Additionally, hardware costs can be decreased by using cloud-based services, where with the help of virtualization, storing and computing capacities can be easily and cost-efficiently adjusted according to the needs, without greatly compromising performance and security (Carpenter 2016). Another important opportunity for early IIoT adopters is providing safer working conditions for workers and improving their productivity. IIoT achieves this by giving them more flexibility, as workers can access valuable data from anywhere on any device. Furthermore, it makes work more enjoyable and engaging as employees will no longer need to perform routine tasks and can focus on other creative and value-adding activities. (O'Halloran & Kvochko 2015, Kagermann, Wahlster & Helbig 2013) Daugherty & Berthon (2015) add to this by stating that "decision making can be devolved to workers empowered by valuable data, while the design and creative process could become more iterative and experimental."

The second phase of new products and services is also a rather big incentive to IIoT adoption. Due to the fact that suppliers of equipment can monitor their products in real-time using IIoT, it is easy for them to deduce when, for how long and how their equipment is used. This opens space for new product and service opportunities and new data-centric business models (Koch et al. 2015). For example, instead of convincing a customer to make a huge investment in new equipment, it will be possible to charge him on per-use principle (O'Halloran & Kvochko 2015).

This could take into account things, such as how long the equipment was used and how demanding tasks it performed, amongst many others. The movement towards increasingly digital business models is substantial to companies as it will enable the creation of additional value to customers through customer-specific solutions. Horizontal cooperation across the value chain and vertical integration, supported by data integrity and analysis, will be at the core of these new business models which will help to better fulfill the requirements of customers. O'Halloran & Kvochko (2015) also highlight the importance of cross-industry partnerships for the purpose of creating new business models. Furthermore, as more products become smart and interconnected, O'Halloran & Kvochko (2015) state that the importance of software will increase, which will act as the "connective tissue for value creation". Therefore, product suppliers will face the opportunity to create software for analyzing customer data, making valuable insights and selling it back to the customers as data monetization services. Carpenter (2016) also highlights the importance of faster flow of information between different levels within an organization that is enabled by the IIoT and its significant impacts on decision making, such as 30% faster product launches.

From the perspective of the equipment supplier, being able to remotely access and continuously monitor their equipment in real-time, or near real-time, during the entire life cycle of the product, has huge implications. For one, it leads to a closer relationship with their customers and a better understanding of how and in what environments their products are used. (Collin & Saarelainen 2016) Furthermore, device and system suppliers can use this information to improve the quality of their products to match the customers' needs even more closely, and offer new values and services that have been previously impossible (e.g. preventive maintenance, Section 2.3.7) (Carpenter 2016). Additionally, unnecessary trips by the service personnel will be a thing of the past, as small issues could be either fixed remotely or maintenance people can guide their customers to solve the problem themselves (O'Halloran & Kvochko 2015). All these are completely unimaginable in the current situation in which, after delivery, the next time suppliers see their products is when they arrive for a service check or repair.

The last two phases are long-term structural changes, which according to O'Halloran & Kvochko (2015), will occur approximately three to four years after IIoT adoption. The idea of "outcome economy" is that suppliers search for new value creating opportunities in which they help their customers to use their products in a way that meets certain outcomes. In other words, companies compete to deliver quantifiable results for the customer and sell measurable outcomes instead of products and services. This will require businesses to disrupt their own markets and shift from the traditional competing grounds of providing high-quality products and services at competitive prices. The outcome economy phase is harder to reach than the first two phases but will have many implications for businesses, and will provide a differentiating factor. Based on the collected sensor data, businesses will be able to more precisely calculate costs and manage risks, as well as track all phases that provide the customer with the promised value. (O'Halloran & Kvochko 2015, Daugherty & Berthon 2015)

The final phase that companies go through after adopting IIoT solutions is the phase when different business processes become increasingly autonomous and less dependent on human intervention. This will take the most time to achieve and will require huge improvements in sensor intelligence, hardware and software. At this stage, devices will get a sense of understanding of the physical world around them in a similar way to humans and will remember their own history (Sadeghi & Wachsmann 2015). Vertical integration will be achieved to such a level that would enable end-to-end automation, where smart systems would make all the decisions based on the ubiquitous data, under human supervision. A few advantages of this phase will be the continuous sensing of demand, the optimization of resources and the reduction of waste. (O'Halloran & Kvochko 2015) This idea is further covered in Section 2.3.7.

Some of the major opportunities brought by the IIoT are summarized in Figure 8.

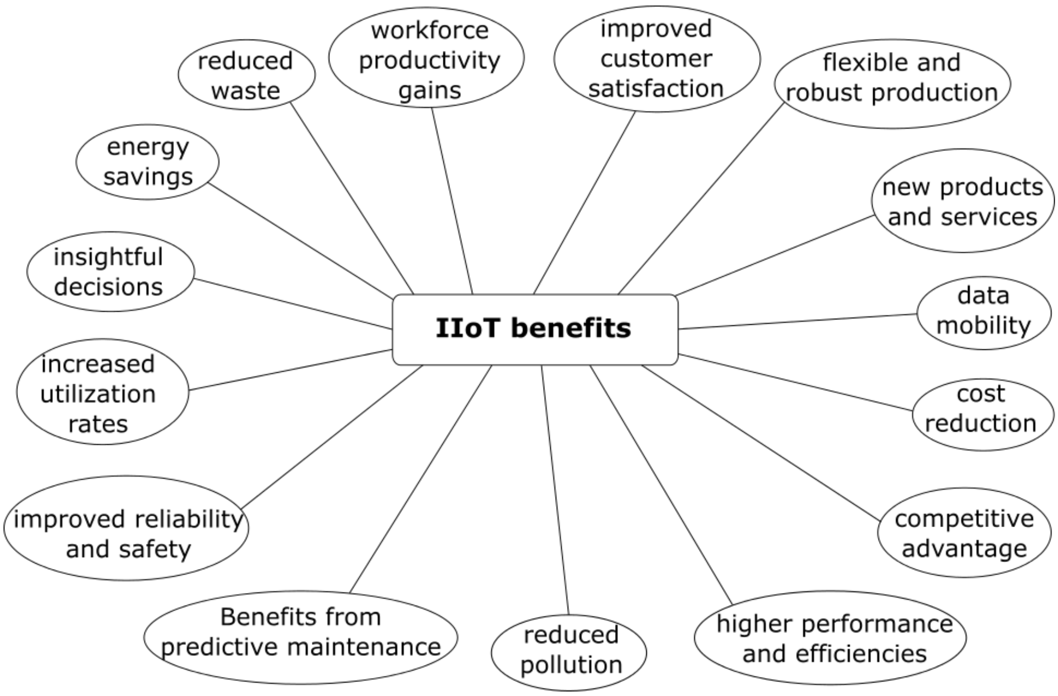


Figure 8: Some benefits of IIoT.

2.3.6 Risks, threats and challenges of IIoT

Though having the potential to provide huge opportunities, as noted in Section 2.3.5, IIoT by no means guarantees them. Additionally, there are various risks, threats and challenges that businesses and governments need to first overcome before realizing the full potential of IIoT. There is one thing that is, however, certain: the industrial internet of things is set to disrupt businesses. Companies that fail to act quickly are facing risks of losing their momentum, as well as market share, to faster players and new market entrants (*Industrial Internet Insights Report* 2014). Organizations must, therefore, focus on their core values and strengths, reevaluate their strategies, and transform their approach to be IIoT-enabled, customer-centric and service-oriented.

It is, therefore, essential for businesses to explore the new opportunities IIoT presents to them, weigh the risks and think critically. It is equally as important for businesses to identify the players in this new ecosystem, and to decide whether forming a partnership is appropriate (O'Halloran & Kvochko 2015).

As emphasized by the executive director of IIC (Soley 2015), one of the major concerns about the industrial internet of things is security, due to its direct connection to safety. Previtali et al. (2016) notes that a physical isolation of industrial networks from the outside world has previously played a significant role in the overall security of critical industrial control systems. Though far from foolproof, as demonstrated by Stuxnet (Langner 2011), "air-gapping" does greatly diminish the cyber attack domain. The industrial internet of things radically changes this approach by exposing industrial networks to the global network, making them remotely accessible by both authorized people and rogue actors. Due to the fact that IIoT systems are responsible for controlling physical processes, a successful cyberattack can cause physical damages to the production plants, and to the environment and people around, or at the very least lead to the interruption of operations, production plants' downtime and economic losses. (Previtali et al. 2016, Schrecker et al. 2016) Bruner (2013, p.9), however, emphasizes that, even though a network might be thought to be isolated, "contraband connectivity invariably makes its way into the system". Therefore, he suggests that designing the system with connectivity in mind, instead of marking it as isolated, can lead to better security. According to an expert on networks of big machines at Cisco Systems, "there is nothing more secure than IP", due to the huge numbers of attacks it has been under for the past decades (Bruner 2013, p. 13). Initiations for developing common security frameworks, such as the one by IIC (Schrecker et al. 2016), will certainly have great impacts on the security issues related to IIoT and reduce the weight of security as a barrier to its adoption.

Privacy is another major concern. The new ways of interconnecting devices also create new vulnerabilities that can be exploited by hackers to gain access to confidential data (Soley 2015). A leakage of business data can cause significant losses of intellectual property, create bad reputation and lose customers. Furthermore, as stated by Sadeghi & Wachsmann (2015), the privacy of employees may be violated by using Big Data analysis.

Another major challenge and barrier to adoption that needs to be addressed is the interoperability of systems from various vendors (Daugherty & Berthon 2015, O'Halloran & Kvochko 2015). As mentioned by O'Halloran & Kvochko (2015), operational technology systems currently in use in industries follow the silo mentality, i.e. automation systems from different manufacturers do not tend to share data between each other. Apart from this causing undesired system complexities and poor cost-efficiency for the customer, the entire idea behind IIoT of interconnecting systems is defied if various systems cannot communicate with each other. Furthermore, even if interoperability is achieved, questions, such as "Who owns the data?" and "Who can use the data?" must be answered. Therefore, this mentality will have to be changed and a number of standards and industry requirements will have to be developed in order to support and push towards the integration of solutions from different vendors in the future. (Soley 2015) O'Halloran & Kvochko (2015) highlight that the long life-cycles and high prices of industrial equipment will further complicate this issue and slow down the change towards seamless interoperability between systems from different vendors.

Other important hurdles that slow IIoT adoption include organizational uncertainty on the return on investments in new technologies, which are typically immature and untested; the lack of rules and laws on data governance across geographical boundaries; the deficiency of properly educated people for the purpose; and the challenge of educating and convincing businesses to adopt IIoT. Bypassing these obstacles will require proper leadership, investments and collaboration between governments and businesses. (O'Halloran & Kvochko 2015, Koch et al. 2015)

Challenges from the communications point of view should also not be overlooked. O'Halloran & Kvochko (2015) point out an important difference between the internet of people and the industrial internet: real-time constraints. The real-time constraints for the internet of people are orders of magnitude larger than that for machines (a few seconds vs. sub-milliseconds, respectively). Reliability in IIoT communication networks has to also be much higher than for the common internet of people, as an unexpected error can have a direct impact of great significance on the physical world. This strong bias in the industrial world towards real-time, reliability and availability will play a major role in shaping the industrial internet of things. (O'Halloran & Kvochko 2015)

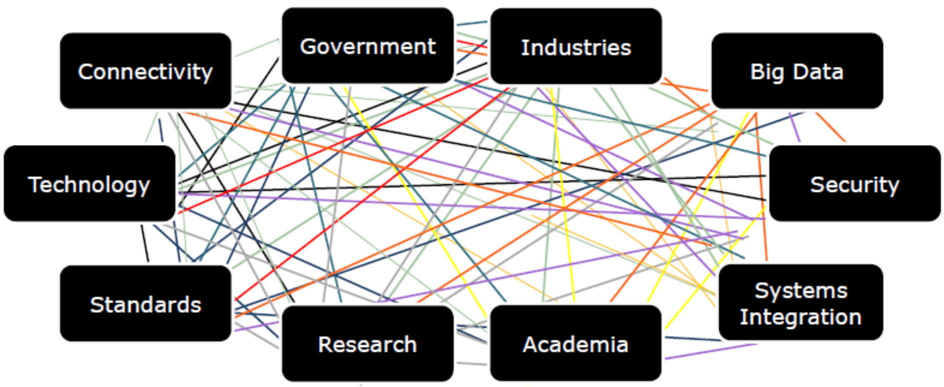


Figure 9: Roadblocks to IIoT. (Soley & Hoske 2015)

Figure 9 summarizes the main roadblocks to widespread adoption of IIoT, according to the IIC. There are a number of different organizations (black boxes) that contribute to bringing IIoT forward but the problem is that they work independently. Dr. Richard Soley highlights that in order to achieve widespread adoption of IIoT, these organizations need to start working together, and that is where ecosystems, such as the IIC, come into play to provide a collaborative environment, as illustrated by Figure 10. (Soley & Hoske 2015)

2.3.7 Applications

The industrial internet of things brings along a number of new application areas and improvements to existing ones. In this section four significant application areas

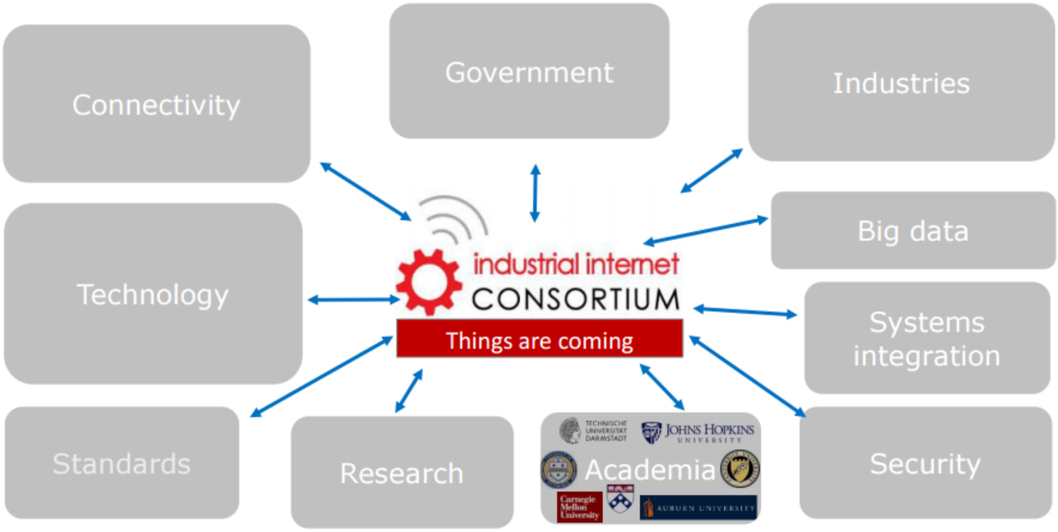


Figure 10: IIC role to widespread adoption of IIoT. (Soley & Hoske 2015)

are discussed that are already in use by companies around the world. These are remote asset monitoring, predictive maintenance, new data-driven business models, and smart factories and autonomous products. These application areas are deeply connected and dependent on each other, for example predictive maintenance would not be possible without remote asset monitoring. (Collin & Saarelainen 2016, p. 61)

Remote asset monitoring

As emphasized by Collin & Saarelainen (2016, p. 61), applications based on remote asset monitoring and remote asset optimization are old inventions, and have been used by industries for a few decades. There are, however, revolutionary changes brought to these by the IIoT with the introduction of cloud services and big data analytics. These enable analysis on large amounts of real-time data and history data, and support making the right decisions quickly. Furthermore, devices become self-aware, self-learning and self-repairing. A case study by the IIC (*Global Manufacturer uses remote access cybersecurity to maintain safety at its manufacturing production zones* 2015) points out that with the help of intelligent devices engineers are able to remotely troubleshoot issues happening on the factory floor from anywhere in the world. This has huge implications to both manufacturers and their partners, as maintenance workers do not need to be sent out every time a problem occurs and therefore, can substantially decrease travel costs and save time. As stated by (Collin & Saarelainen 2016, p. 62), remote asset management and remote asset optimization can hugely influence the productivity; in some cases efficiencies have increased by tens of percent. Furthermore, remote asset updates are essential in the IIoT era, since they can radically change the properties of IIoT devices or repair them if there is a software issue.

With the help of IIoT, remote asset monitoring can be extended to include remote usage monitoring. Remote usage monitoring can tell, for example, who is using a device, where and when the device is being used, and also how is the device being used. Based on this data, it is possible to make conclusions on whether the device is properly used and whether the personnel need more training to learn to use the device more effectively. In the manufacturing industries, remote asset monitoring can be used to obtain real-time data on the quantity of produced products by a piece of equipment and the quality of the produced products, which is very closely related to asset performance management (APM). These data can then be used to improve the quality of existing products and create new products, in order to increase the customer satisfaction. Additionally, suppliers can determine if their products are over-engineered, i.e. if there are any parts and functions of the product that the customer does not use. In case there are, the unneeded parts and functions can be removed, thereby reducing production costs, materials used and waste. (Soley & Hoske 2015) From the point of view of the equipment supplier, in case the customer requests a replacement or repair covered by the warranty of the device, the collected device data can be used to determine whether the device was properly used and if the warranty covers the costs. Figure 11 describes the relation between these different applications, with the lower levels being the base of, and enabling, the upper levels. (Collin & Saarelainen 2016, p. 64)

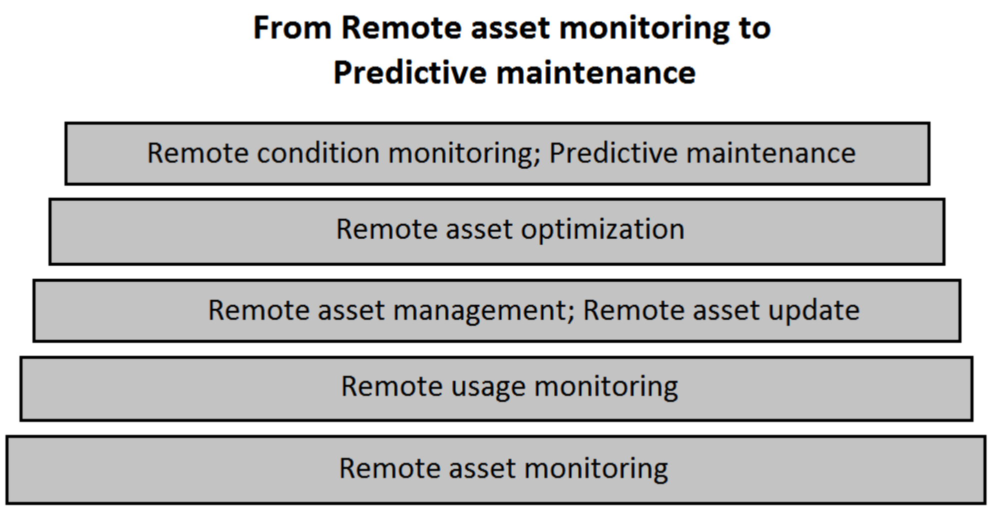


Figure 11: Remote asset monitoring as the base of other important application areas enabled by the IIoT. (Collin & Saarelainen 2016, p. 63)

Predictive maintenance

According to (Rasekh et al. 2016), availability is of the greatest importance in industrial control systems (ICS), due to the huge negative impacts that unavailability can have on people and societies. As a result, maintaining equipment is an essential part that enables the continuous functioning of ICS. The maintenance of equipment can be typically categorized into two main groups: corrective maintenance and preventive maintenance. Corrective maintenance (CM), also know as breakdown or run-to-failure maintenance, occurs after equipment failure and is the action of repairing or replacing the equipment, so that it can perform its original functions.(Ahmad & Kamaruddin 2012) CM is a reactive approach to maintaining equipment because the maintenance is triggered by the unscheduled event of equipment malfunction. CM is also the oldest and most basic type of maintenance, and is very inefficient. As noted over 20 years ago, there is a high risk of machine downtime and the loss of property associated with corrective maintenance. (Tsang 1995) These directly result in production losses and high maintenance cost (Ahmad & Kamaruddin 2012).

The other alternative is preventive/proactive maintenance (PM) which is a lot more advanced way to maintain equipment. It is also the preferred one of the two, as it reduces the aforementioned risks (Chen et al. 2017). Improvements in technology have made this type of maintenance possible, where equipment is maintained prior to failure. PM has traditionally been done by scheduling maintenance for equipment at regular time intervals, either recommended by the equipment manufacturer or set through experience. This traditional approach to PM is known as time-based maintenance (TBM). TBM techniques have their drawbacks in terms of minimizing operational costs and maximizing machine performance, and are hardly applicable to most situations as each machine works in a different environment. A few disadvantages of TBM are that, firstly, maintaining a machine at fixed calendar days does not remove the possibility of the machine breaking down right before the scheduled maintenance. Secondly, performing maintenance on a machine that does not need to be maintained is just unnecessary extra costs to the company. (Ahmad & Kamaruddin 2012)

One of the major expectations of the IIoT is Predictive Maintenance (PDM), or its synonym remote condition monitoring. Compared to the other aforementioned application areas of IIoT, achieving PDM is more demanding, as it requires deeper data analysis. (Jin et al. 2016, Collin & Saarelainen 2016, p. 73) Essentially, PDM belongs to the preventive maintenance group, as it aims to prevent equipment breakdown by maintaining it before a malfunction occurs. Though having the same outcome as the traditional time-based maintenance, PDM offers a whole different approach of how to achieve it. This modern approach is called condition-based maintenance (CBM). (Ahmad & Kamaruddin 2012) Predictive maintenance eliminates the drawbacks of TBM and has the potential to greatly improve operational efficiencies of businesses. As the name suggests, it refers to companies being able to predict when equipment will break down and when it needs to be maintained. This is achieved by analyzing the huge amounts of gathered operational data, made possible by the IIoT, in order to spot irregularities and undesired equipment performance. Maintaining the equipment in this way will largely reduce the unexpected downtimes, which are typically very expensive to industries, and eliminate unnecessary maintenance costs, since the equipment will be maintained exactly when it needs to be. (Jin et al. 2016, Collin & Saarelainen 2016, p. 73) Some of the major benefits of predictive maintenance to businesses are summarized in Figure 12.

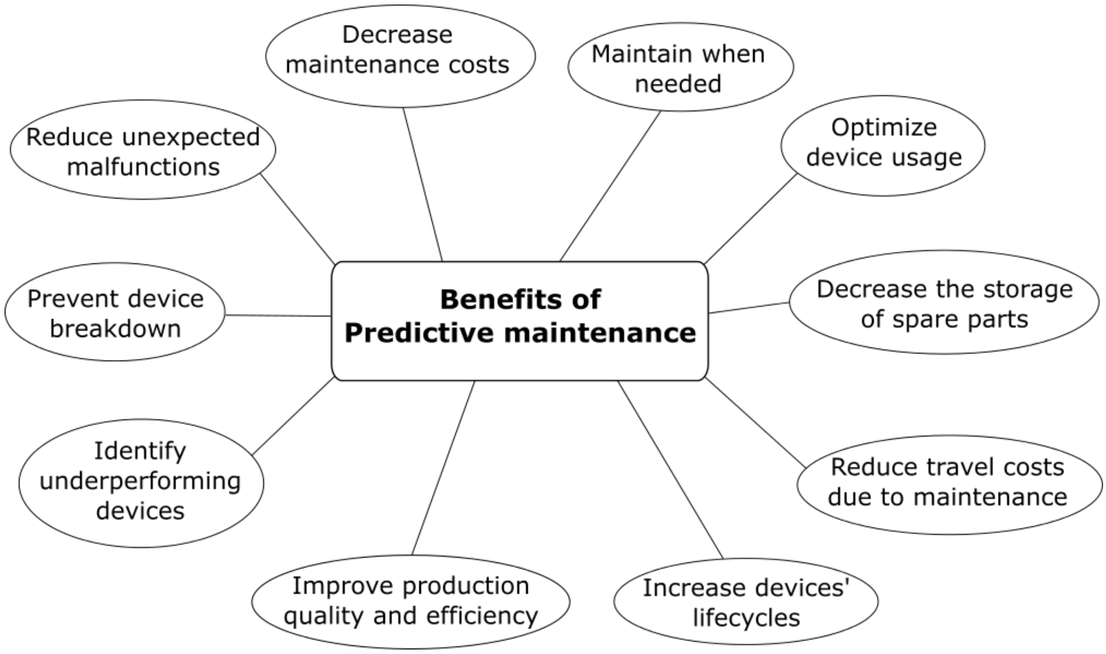


Figure 12: Some of the benefits of predictive maintenance. (Collin & Saarelainen 2016, p. 75)

New business models

As mentioned previously in Section 2.3.5, IIoT will lead to the creation of new business models, as a result of the continuous, real-time data flow between suppliers and their customers. As Collin & Saarelainen (2016, p. 81) highlight, this data flow can lead to the termination of the traditional sales activities and the complete transformation of business models. Suppliers of equipment might come to the conclusion that it no longer makes sense to sell their products as previously but sell products-as-services instead. The billing could be based on measurable variables made possible by the IIoT, such as machine operating hours, throughput or reduction of production halts. Customers will also benefit from the product-as-a-service concept because they will no longer need to make huge initial investments in equipment. The manufacturer will retain the ownership of the asset and can offer to provide all the necessary maintenance, services and repairs. (Gorbach & Polsonetti 2014) This will have a direct impact on economies, as it will be easier for new businesses to enter the market and to compete with existing businesses. Furthermore, organizations can explore new after-sales services that they can offer to their customers, such as regular software updates of the production systems that can be managed remotely. Suppliers could also offer to their customers a variety of applications and user interfaces that use the gathered data and improve the user experience. Finally, another opportunity that cannot be overlooked is selling the enormous amounts of collected data as a anonymous mass, which has been filtered and thus, confidential information has been removed. This data can be used, for example, by new market entrants, that do not have process data accumulated of their own, in order to optimize their own processes.(Collin & Saarelainen 2016, p. 82)

An automated, reliable and comprehensive documentation, enabled by the collection of sensor data and analytics, is a substantial new service that can be sold to customers. As stated by Collin & Saarelainen (2016, p. 83), in many industries the documentation of the different manufacturing phases is a significant requirement related to quality control. Since each phase of the manufacturing process produces data that is shared via the IIoT setup, it is possible to automatically create a digital documentation about each product individually. Therefore, products will "know" themselves and "remember" how, where and when they were produced, and this information will be easily accessible by the customers. (Collin & Saarelainen 2016, p. 83)

Smart factories and autonomous products

Manufacturing industries have long aimed toward the development of smart factories, which have a key role in the Industry 4.0 idea. Smart factories refer to manufacturing facilities in which each device is equipped with sensors and devices are connected to the same network, to the same analytics system and to each other, with each device having its own unique identifier. Smart factories, therefore, become adaptable to every possible situation, and reduce the need for human intervention, such as monitoring and basic control operations. Each device in the smart factory will be continuously aware of itself, its contribution to the production process and its relation to other devices and parts of this process. As a result of the communication between devices, individual devices will also know what manufacturing phases occur before and after them, and will be able to react and adapt to external events. (Collin & Saarelainen 2016, p. 86) For example, devices would be able to communicate with each other to automatically determine which one of them could execute a given task the quickest; or in case of a sudden malfunction of a device, which will be highly unlikely but still possible despite predictive maintenance, other devices will immediately know about it and will automatically re-plan the production path so as to not cause production jams and optimize the process under the given circumstances. In such scenarios, smart factories will be able to themselves schedule maintenance works for times when there will be the least negative impact on production. According to (Collin & Saarelainen 2016, p. 86), the intelligence due to IIoT can be extended even further to cover products under production. Products from a very early stage of the manufacturing process could be aware of what they are supposed to become, as well as the phases and the order they would have to go through these phases in the production process. The entire manufacturing could be transformed from the traditional approach, in which products are commanded around a variety of production points, to a new approach, in which products command to which production points they should to be taken next; provide feedback on the quality of the work done to them; and alarm if the quality requirements were not met.

Overall, smart factories will be flexible and self-organizing systems, which enable automatic production without the need of human involvement. The entire production process will be easily customized by the factory itself according to customer needs, and optimized in real-time to achieve the best outcomes in the shortest time possible. This will all be done in a much more environmentally friendly manner because the IIoT will drive down the waste of resources and raw materials. Furthermore, due to the vertical integration in supply chains enabled by the IIoT, smart factories will be able to order the exact amount of needed raw materials, so that they arrive exactly when needed and thus, decrease the costs of storing them. Additionally, they will handle the logistics of the ready products.(Collin & Saarelainen 2016, p. 87)

2.3.8 Market readiness for IIoT

Despite the huge advantages of IIoT and most of the technological ingredients being ready to support its adoption, IIoT solutions are being very slowly adopted by manufacturing industries (Drath & Horch 2014). In a report by Accenture (Daugherty & Berthon 2015), a key finding was that many CEOs actually feel overconfident about their readiness to adopt IIoT. This might partially explain the slow adoption rate, as CEOs believe they can quickly transform when the time is right. Despite this feel of readiness, according to the Accenture report, a stunning seventy-three percent of company leaders confess that their businesses do not have any concrete strategies and plans for progressing in the field and admit that they do not see the big picture and do not comprehend the impacts of the IIoT on their business models and the long-term implications that it imposes on their industries. These conclusions are also supported by O'Halloran & Kvochko (2015), whose findings are presented in Figure 13.

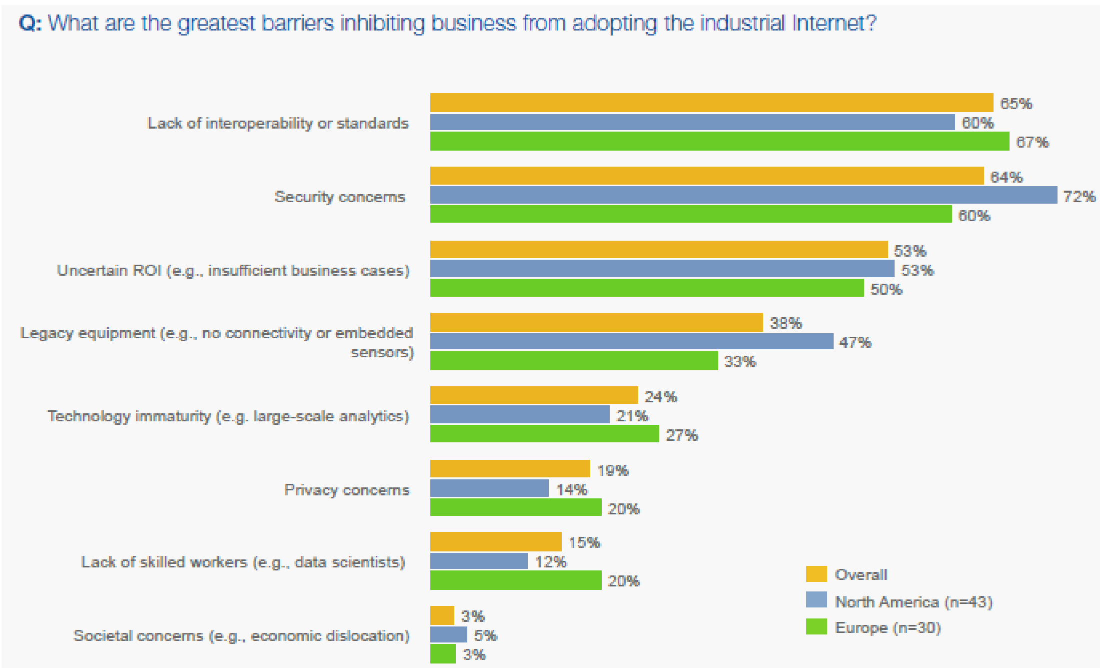


Figure 13: Key obstacles to IIoT adoption. (O'Halloran & Kvochko 2015)

Another key finding of the Accenture report (Daugherty & Berthon 2015) is that many countries are not properly setting up the environment and laying down the foundations needed to spur IIoT adoption. According to O'Halloran & Kvochko (2015), it is essential that industries, governments and academia collaborate on Research and Development to solve the major technological risks and challenges related to security, privacy and interoperability. Enabling this collaboration is the aim of the Industrial Internet Consortium.

2.3.9 ABB's Internet of Things, Services and People

ABB has been one of the early adopters and drivers of the IIoT. It extends, however, the aforementioned concepts of Internet of Things (IoT) and Industrial Internet of Things (IIoT) to include the role of services and people, and they call it the Internet of Things, Services and People (IoTSP). As stated by Schönrock (2016), this integration of people and services into the IIoT concept is what differentiates ABB from its competitors and strengthens ABB's position as a leader in technology. It also plays a major role in ABB's Next Level strategy in which the focus is on customer needs.

ABB Ability

The idea behind the ABB Ability is to bring together all of ABB's digital products and services for the purpose of creating new business value to ABB's customers by utilizing the power of IoTSP. According to (Schönrock 2016), ABB has the "world's largest installed base of connected industrial devices" and is the world's leader in securing and using data obtained from these devices. An example of an innovative product, resulting from ABB Ability, is the ABB smart sensor.

Smart sensors

ABB's smart sensors are focused on adding new capabilities to existing equipment. The idea behind the product is to offer a much cheaper alternative to replacing old and functioning equipment with costly new IIoT-enabled equipment, while still providing companies with the benefits and opportunities of the IIoT. The wireless, pocket-sized sensor, shown in Figure 14, is simple to attach directly to the frame of old, low-voltage motors, and measures vital physical quantities of the motor, such as vibrations, sound and temperature. The data is wirelessly transmitted via an ABB gateway or a smartphone to the cloud where it is analyzed and the results are send back for optimization purposes and predictive maintenance. According to ABB, the sensor can reduce unplanned downtimes by as much as 70 percent, extend the lifetime of the motor by up to 30 percent and improve the energy efficiency by up to 10 percent. (ABB 2016)

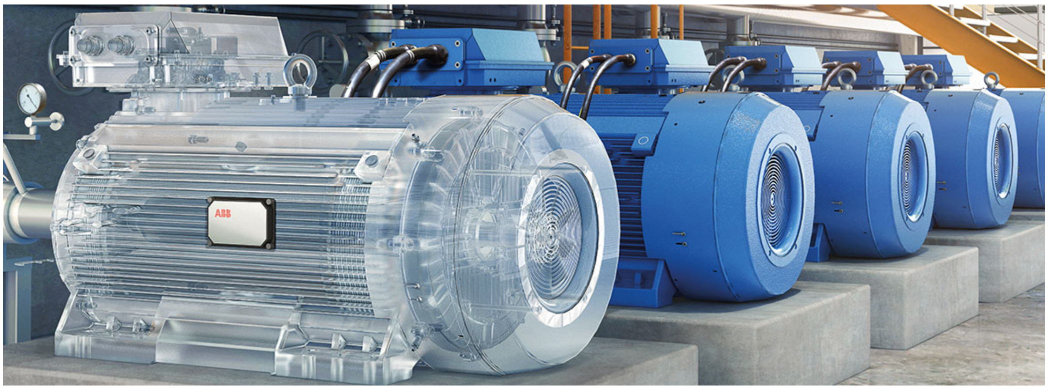


Figure 14: ABB's smart sensor. (ABB 2016)

2.4 Process data visualization

As described in detail in Section 2.3, the central idea behind the IIoT is the abundant collection of data, applying sophisticated Big Data algorithms to process the data and using the resulting insights to make intelligent decisions at different levels within organizations. All of this will, however, have no value without properly presenting the data to the right people and machines so they can make some sense of it. Currently, people are still the ones responsible for making high-level decisions in companies but even in the future when machines are increasingly more often able to make decisions themselves, people will still want to be involved when needed, to supervise and to control.

The important role of visual representations in the decision making process has been broadly emphasized in the past (Tufte 1990, Eden & Ackerman 1998, Rohrer 2000, Tan & Platts 2003, Mazza 2009). As argued by Sackett et al. (2006), "visual representations can facilitate problem-solving and discovery by providing a structure for expressing and communicating meaning of highly abstract data." They further state that visualization allows decisions makers to use their natural spatial abilities for solving a problem. It is, therefore, essential for the visual representation of data to be intuitive and easily understandable to the person it is presented, in order for him to be able to quickly draw the correct conclusions and make the right choices. An important note, however, as stated by Gregory (2015), is that "just because a technique displays data in a graphical form does not mean the display will be useful". To prove this point, Figure 15 shows a visual representation of a set of objects which (purposefully) misuse human visual perception and add confusion. Therefore, as emphasized by Vitulano et al. (2005, p.111), an essential requirement that has to be met by every visualization technique is that it enables a "rapid, accurate and effortless visual exploration".

There are a number of advantages associated with proper visualization. One of the most important one is the widely known English idiom - "a picture is worth a thousand words" - meaning that a visual image can very quickly and efficiently provide information that could sometimes even be impossible to describe with language. Mazza (2009, p.4) emphasizes that apart from enabling information to be

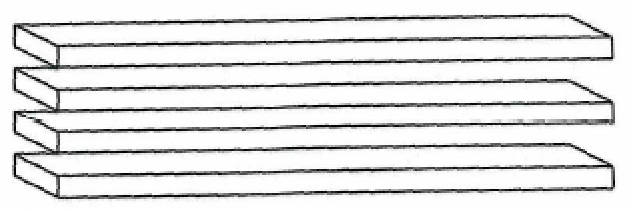


Figure 15: Three beams or four beams? (Ward & Grinstein 2010, p.74)

perceived more easily, a well-structured visual representation also allows for parallel processing of several items of information. Proper visualization can therefore present huge amounts of data to people in an easily understandable form. It can reveal hidden patterns and emergent properties that would have otherwise been left unnoticed. The perception of patterns is typically the first crucial step for developing new insights and solutions to existing problems. (Ware 2012, p.3).

Section 2.4.1 describes the process of understanding data and where visual representation fits in.

2.4.1 The path to wisdom

In his essay (Jacobson 2000), Shedroff gives the name "continuum of understanding" to the process of understanding data. He claims that the "continuum of understanding" consists of four distinct phases, as illustrated in Figure 16, and he describes how information is generated from data, which is then transformed into knowledge and lastly, into wisdom.

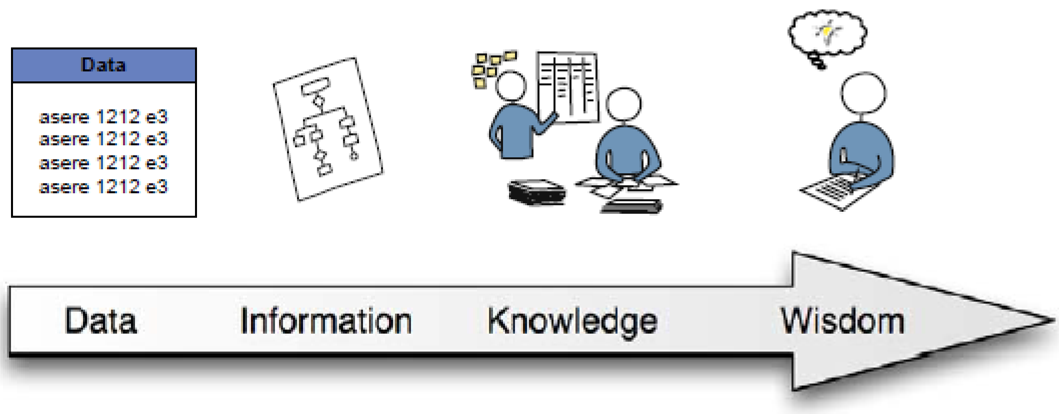


Figure 16: The continuum of understanding according to Nathan Shedroff. (Mazza 2009, p.9)

Data is the raw substance and as described by Mazza (2009), it lacks meaning by itself. However, data is essential as it creates the base for information and for the communication processes. For example, the numerical values of data recorded from several thermometers around a house do not in themselves have much meaning and are not sufficient for a communicative process. In order to obtain some meaning from the data, it must be first processed, structured and presented in a meaningful way. This type of manipulation of data transforms it into information. (Mazza 2009) Continuing with the example, the temperature data can be organized into a table in ascending order to present the minimum and maximum values of different locations in the house.

Information is transformed into knowledge when it is combined with previous experience. As described by Mazza (2009), obtaining experience translates into acquiring knowledge, which is the crucial component of understanding things. For example, a habitant of the house might read from the table that the minimum temperature of the previous night was 17 degrees celsius. Based on his experience, he knows this is rather cold temperature. Mazza (2009, p.9) notes that developing knowledge should be the main goal of any communication process.

Wisdom is the last and highest phase of comprehension. Mazza (2009, p.9) defines it as "the stage in which a person has acquired such an advanced level of knowledge of processes and relationships that it is then possible to express qualified judgment on data". According to him, wisdom cannot be taught but everyone individually achieves it through the careful study and interpretation of knowledge. An example of this with the household temperature would be claiming a thermometer to be broken due to abnormally high temperature readings.

According to Mazza (2009, p.9), information visualization occupies the place between data and information. It provides the means, such as methods and tools, for the organization and representation of data that transform it into information. Until approximately two decades ago, visual representation of data was considered to be part of a much bigger discipline called "human-computer interaction" but it is nowadays considered its own discipline. Card, Mackinlay & Shneiderman (1999) define this discipline as "the use of computer-supported, interactive, visual representations of data to amplify cognition". In practice, the human cognitive system creates information based on the presented data (Mazza 2009, p.10).

2.4.2 The four stages of visualization

According to Ware (2012, p.4), data visualization itself is a process that can be broken down into four distinctive basic stages which are connected via a number of feedback loops, as shown in Figure 17. The four stages consists of the following activities:

1. Collecting and storing data from the physical world. The collection is usually achieved vie sensors that measure physical quantities.

2. Preprocessing the collected data in order to transform it into a form with which it is easier to operate. Typically the amount of data is reduced, for example by applying filters, in order to eliminate noise and to reveal the data of interest.

3. Visualizing the data of interest using computer algorithms that create an image on a screen. Adding interaction to the environment, such as the possibility to highlight, select and hide information, can aid human perception and understanding.

4. Perceiving what is visualized via the human perceptual and cognitive system.

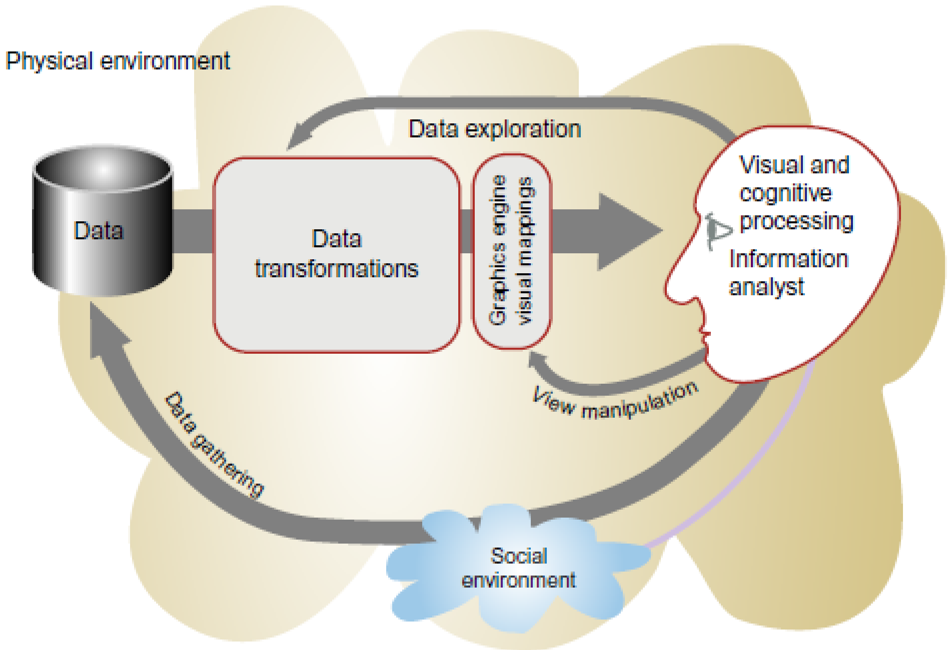


Figure 17: The visualization process. (Ware 2012, p.4)

As shown in Figure 17, the three feedback loops are data gathering, data exploration and view manipulation. The data gathering feedback loop refers to when the information analyst decides that more data is needed for his purposes. The data exploration feedback controls the preprocessing stage of the process which happens prior to visualizing the data. The last feedback loop - view manipulation - refers to the interactivity between the information analyst and the visual representation, such as rotate, zoom and dissect a 3D model of an object. It is also important to understand that both the physical and social environments are involved in the visualization process, and can affect how the data is collected, visualized, perceived and interpreted. (Ware 2012, p.5)

This thesis is focused on the third stage: visualizing the data of interest using computer algorithms. According to Sackett et al. (2006), two of the key challenges in the field of information visualization are producing visual representations that employ the capabilities of human visual perception and enhance information apprehension. A good starting point in addressing these challenges arises from the description of visualization by Green (1998) as "a joint function of computer graphics and perception", from which it directly follows that it is essential to first understand human perception in order to be able to successfully visualize information to people. This needs to be done by designing displays that take advantage of the capabilities and overcome the limitations of the human visual perception.

2.4.3 Understanding human visual perception

Friedhoff & Benzon (1989) divide visual processing into two domains: conscious and preconscious vision. As the names imply, the conscious visual process involves activities, such as thinking and analyzing what is seen, whilst the preconscious visual process (also known as pre-attentive visual process) is solely performed by the human eye, prior to the active processing done by the human brain. Gershon (1994) describes it in the following way: "The conscious mind receives information after it has been processed by the preconscious visual system". For example, searching for trends from numbers presented in a table requires conscious thinking. On the other hand, representing the same data in a plot and performing the same task invokes mostly a preconscious process, which compared to the conscious process, is much easier and faster (Garrick et al. 2005). Dividing visual processing into this way means that in order to enhance the value obtained from data visualization, the data needs to be presented in a way that maximizes the preconscious visual process. In other words, effective visualization techniques aim to move as much of the visual processing from the relatively slow conscious thoughts to the much faster preconscious instincts. (Ware 2012, p.21)

In early studies, vision researchers discovered that there exists a set of visual properties that the human eye detects very rapidly, accurately and in parallel by the low-level visual system. The name given to these properties was pre-attentive properties due to the belief that their detection precedes the conscious focused attention. Though it was later found that focusing also plays a role at this early stage of detection, the term pre-attentive properties is still used because it describes the speed and ease with which these properties are detected. (Ware 2012, p.152) In general, properties that can be detected in large multi-element displays in under 200 to 250 milliseconds fall into this group. This leads to the conclusion that specific information can be processed rapidly and in parallel by the low-level visual system.

Some of the most common examples of visual properties that have been identified as pre-attentive are color, size, flicker, orientation, shape, texture, width and brightness (Garrick et al. 2005, Ware 2012, p.154). An important note is that pre-attentive properties are not all equally strong. As emphasized by Ware (2012, p.155) "there are degrees of popout". According to him, the pre-attentive properties that have the strongest effects are based on color, orientation, size, contrast, and motion or blinking. Additionally, the degree of popout varies also within a property, with larger differences being easier to detect.

According to Ware (2012, p.154), all pre-attentive properties belong to one of four groups: color, form, motion or spatial position. These are discussed below:

Color perception

Color is one of the strongest visual properties in human visual perception (Garrick et al. 2005, Ward & Grinstein 2010). Color is nowadays used in many visualizations to represent a specific value or a range of values. The proper usage of color can be very helpful in perceiving information and can have a very positive impact. Misusing color can, however, have just as significant negative impacts. It may cause confusion and misinterpretation of data, and can lead to serious consequences due to wrong decisions.

The three color properties that are naturally distinguishable by the human eye are hue, brightness and saturation. More specifically, hue is the property of color which is described with names, such as "green", "yellow", "red", etc. Brightness and saturation are properties related to each other that describe the intensity of a specific color (Mazza 2009, p.35). These properties can be seen by the color bands presented in Figure 18. (Garrick et al. 2005)

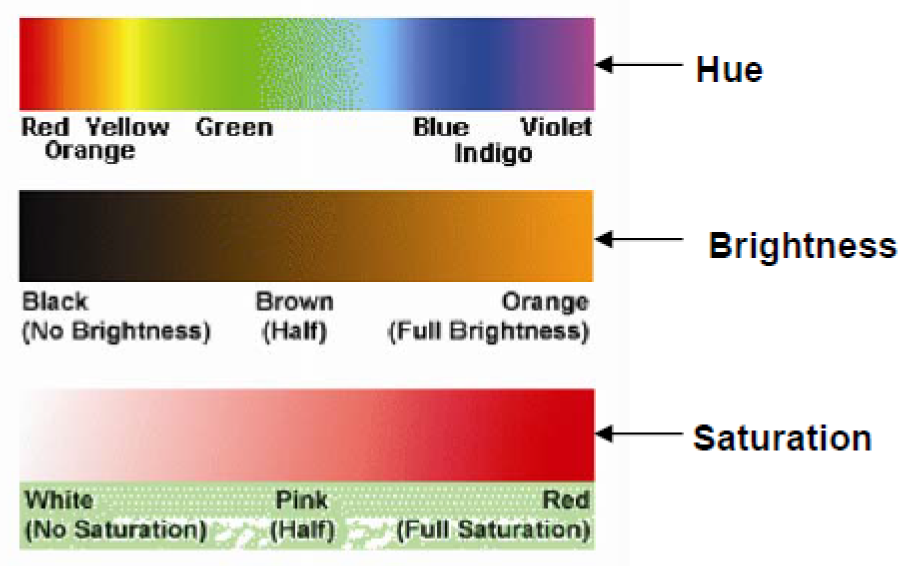


Figure 18: The three naturally distinguishable properties of color by the human eye. (Garrick et al. 2005)

Hue is determined by the prevailing wavelength of light reflected from an image, which enables the human eye to identify colors such as blue, red or green. Due to the structure of the human eye, in which hue is a retinal variable, people instantly and effortlessly detect differences in hue. Therefore, elements with no natural order are most easily differentiated using different hue values. (Garrick et al. 2005) This is illustrated in Figure 19 in which the reader has to count how many 9s there are. In part (a) of the figure, detecting the 9s requires the reader to sequentially scan through all the numbers, which is quite slow. Coloring the 9s in red, as shown in part (b), simplifies and speeds up the counting process because the 9s pop out from their surroundings, making them much easier to detect.

According to Brown et al. (1995), the characteristics of the cones in the human eye have a significant impact on how hue should be used for visualization purposes. Blue-sensitive cones are the least common, and thus, changes in blue are very hard to detect, meaning that blue color must not be used to communicate critical information (Dix et al. 2004, p.136). The much more even distribution of blue-sensitive cones around the retina in comparison to other cones also implies that blue color is suitable for displaying large areas and backgrounds but is not useful for displaying details.

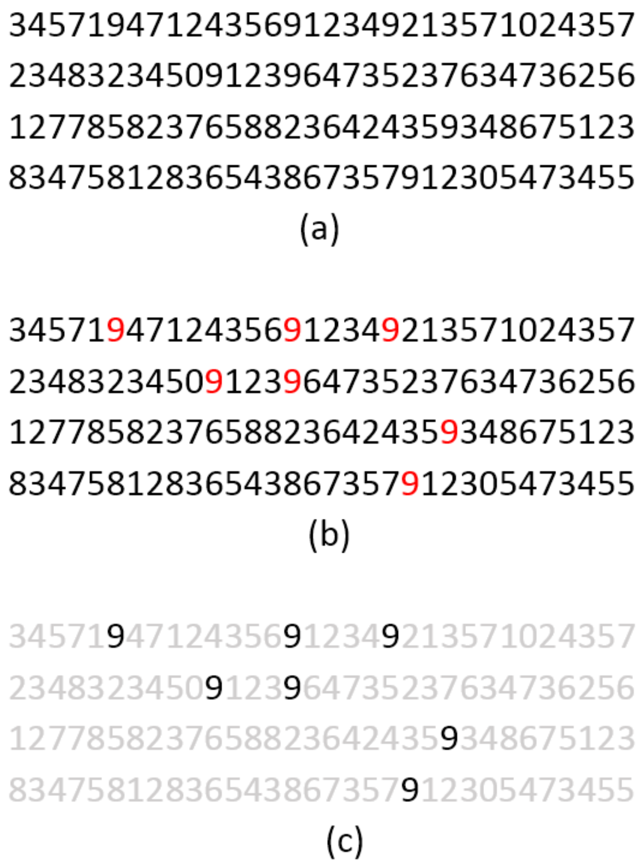


Figure 19: The color properties hue and brightness are processed pre-attentively. (a) Counting the 9s requires scanning through the numbers sequentially. (b) Counting the 9s is much easier when their hue is different; the strong contrast between red and black make them pop out from their surroundings. (c) A difference in brightness also has the ”pop out’— effect.

Contrary to this, red and green sensitive cones are much more common and are, therefore, a much better option for highlighting details. (Dix et al. 2004, p.18)

Brightness typically refers to the perceived amount of light coming from a surface in comparison to other nearby surfaces. Contrary to hue, differences in brightness imply order and thus varying brightness is the most intuitive way to represent ordered data. (Garrick et al. 2005, Ware 2012, p. 80) Saturation, on the other hand, refers to the amount of whiteness in the color. The change in intensity is also processed pre-attentively as shown in Figure 19 (c) in which 9s having a stronger intensity pop out from their surrounding numbers.

As stated by Dix et al. (2004, p.18), the average person can distinguish approximately 150 different hues, however by also varying the brightness and saturation levels, a person can perceive as much as 7 million different colors. The authors, nonetheless, emphasize that a person without any training can identify far less colors - in the order of 10. As a result, it is essential that colors used in displays are as distinct as possible.

Ware (2012, p.21) suggests using what are considered to be the six primary colors: white, black, red, green, yellow, and blue. However, when selecting colors it is important to consider common conventions and user expectations. For example, the colors red, yellow and green are typically associated with the meaning of stop, standby and go, respectively. As such, it is advisable to use red color as an emergency signal and for alarms; yellow color for standby and as an auxiliary function; and green for normal operation. One should be careful to not violate these conventions without a good reason. (Dix et al. 2004, p.136) Furthermore, as emphasized by Mazza (2009, p.21), using color requires special attention as it is the only pre-attentive property whose perception can be influenced by cultural, linguistic and physiological factors. Dix et al. (2004, p.136), for example, point out that in western countries red is associated with danger and warnings but in China it is translated as happiness and good fortune.

Form

Some of the preattentive properties of form according to Mazza (2009, p.36) are orientation, collinearity, length, width, size, curvature, spatial grouping, blur, added marks and numerosity. These are presented in Figure 20.

Motion

According to Ware (2012, p.155), the two most effective preattentive properties of motion are flicker and the direction of motion. As claimed by Mazza (2009, p.38), both of these are very powerful in getting a person's attention and are suitable for situations where an immediate user intervention is required.

Spatial position

Mazza (2009, p.36) lists three preattentive properties of spatial position: two-dimensional position, stereoscopic depth and concavity/convexity. As emphasized by him (Mazza 2009, p.21), spatial position is one of the most powerful and accurate tools to represent quantitative information and is thus, commonly used in scientific data graphs. Stereoscopic depth is used by people on daily basis to preattentively perceive depth and as a result determine distance for example. It is enabled by the two eyes in humans which capture images from slightly different positions and angles, and which are then processed and combined by the human brain. Concavity and convexity are perceived as a result of the difference in the shading of an object. It is important to note that computers are capable of reproducing the feeling of three dimensional space onto a two dimensional surface, such as a monitor, using the aforementioned techniques. For example, Figure 21 illustrates how the concavity and convexity effects can be achieved simply by using proper shading, which is preattentively perceived.

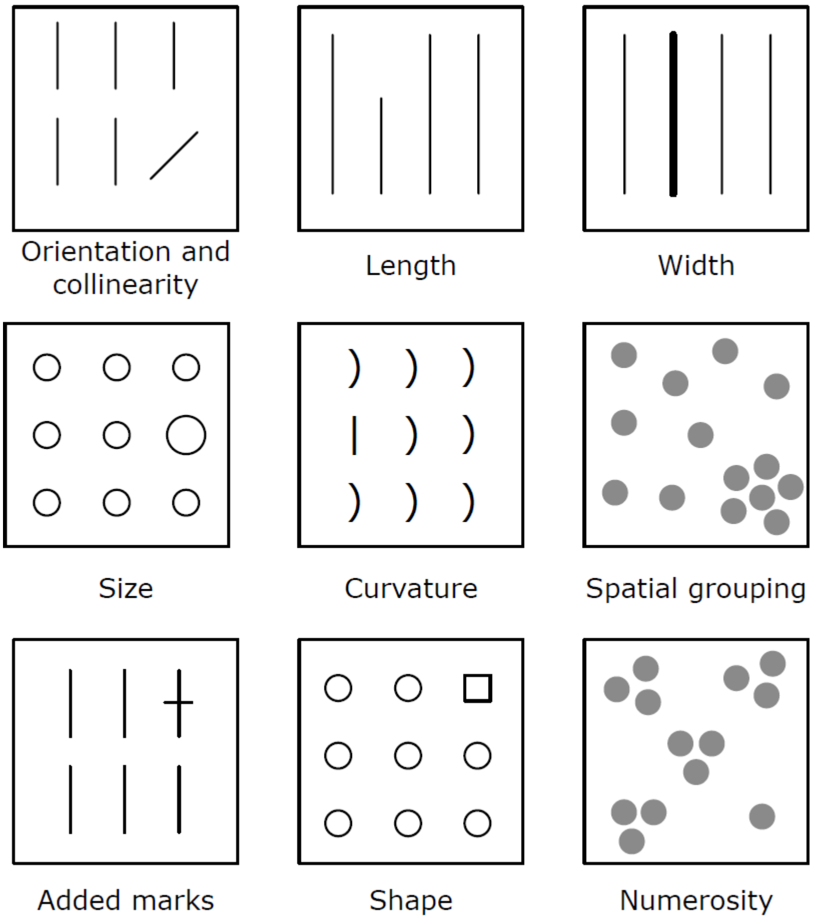


Figure 20: Pre-attentive properties of form. (Mazza 2009, p.37)

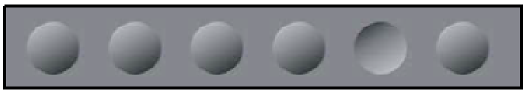


Figure 21: Pre-attentive properties of concavity and convexity. (Mazza 2009, p.37)

2.4.4 Designing visual representations

There are a number of important things that need to be considered when designing visual representations. First of all, as emphasized by Mazza (2009, p.35), information mapping using pre-attentive visual properties is retained in the short-term memory of the human brain. Due to the limited capacity of this memory and the very short amount of time for which it is held (a few seconds), designers of visual representations should not expect users to remember more than nine pieces of information at once. Studies have shown that less than five are ideal. (Mazza 2009, p.35) For example, Ware (2012) suggests that designers use at most eight distinct hue values, four distinct orientations, four distinct sizes, and ten distinct values for all other visual properties. Few (2012), on the other hand, undertakes a more cautious approach and suggests a limit of four distinct values for each visual property.

Secondly, it is crucial to make sure that when combining multiple different pre-attentive properties the result is not non-preattentive. According to Ware (2012, p.157), the "preattentive symbols become less distinct as the variety of distractors increases". In fact, studies have shown that there are two important aspects that determine how well something stands out pre-attentively. These are the degree of similarity between the target group and the non-target group, and the degree of similarity within the non-target group. (Quinlan & Humphreys 1987, Duncan & Humphreys 1989) Figure 22, shows a poor combination of color and shape which makes it hard to detect the target (a red circle). This is an example of a conjunction search in which the target has two features: red and circle. The problem arises from each of the distractors (blue circles and red squares) having one of the aforementioned features, causing the human visual system to not have a distinct visual property to search for when locating the target. Removing either one of the distractors will make the detection process pre-attentive.

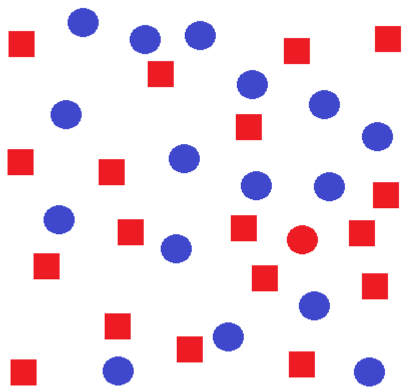


Figure 22: A poor combination of preattentive properties color and shape resulting in a non-preattentive process of detecting the red circle.

Thirdly, Ware (2012, p.168) emphasizes the importance of understanding natural order in visual properties prior to the design of visual representations. He states that some of the pre-attentive properties have a naturally built-in order but others do not. For example, as stated by Ware (2012, p.22), generally it is not a good idea to represent quantitative attributes using the primary colors/hues. This is first of all because hue is not a naturally ordered visual property (Does red come before or after blue?) but also because there might not be enough primary colors. On the other hand, as stated by Garrick et al. (2005), differences in intensity do imply a natural order. For example, in Figure 19 (c), one can describe the 9s as having higher intensity. The visual properties that exhibit a natural order, such as size, length and brightness, as stated by Ware (2012, p.168), increase continuously and are referred to as monotonic. For the aforementioned reasons, visual properties that exhibit a natural order are very useful for expressing quantitative data while being processed preattentively.

For using hue to represent quantitative data, however, he points out that a convention on a color scale, such as the rainbow color scale, can be applied (if well explained). The result will, however, no longer be a pre-attentive process.

Taking these considerations into account, the low-level visual system of humans can be effectively used in visualization to draw the attention to certain areas of interest in a display. This method, nonetheless, requires that visual properties are mapped to data attributes in a way that harnesses the strengths of the human visual system and suits the purpose of analysis. Meanwhile it is substantial to avoid visual interferences, such as the aforementioned conjunction search example, that could hide information. (Ward & Grinstein 2010, p.91)

2.4.5 IIoT impact on process data visualization

As outlined in Section 2.3, the IIoT wave is bringing with it an increasing amount of collected data. Ideally, authorized people should be able to access this data remotely via the Internet from anywhere around the world on both mobile and desktop devices. This means that processes will no longer need to be monitored and controlled only from the central control rooms as in the past or via the slow and lengthy process of opening virtual private network (VPN) connections. Anyone with the rights to access the data will be able to do so remotely as long as connected to the Internet. As a result, mobile will be the keyword in the future.

Data visualization will be directly impacted by the IIoT revolution as it provides the means to display the avalanche of gathered data in a meaningful way. Apart from the need to improve at first the previously developed desktop visual representations, the move to mobile will require the development of new mobile friendly applications for data visualization purposes. In the past, developing native mobile applications has been the commonly accepted way to achieve certain functionalities, however, there are a number of drawbacks with this approach. Firstly, there many different operating systems for mobile devices which are written in various programming languages. This directly implies that the same application will need to be implemented for the use on different operating systems. Doing this can be very expensive and choosing only one platform will dismiss a large number of potential customers. (Corral, Sillitti & Succi 2012) Secondly, mobile devices do not typically have enough computing power to perform complicated tasks, such as 3D rendering, and therefore, it would be a great advantage if the computing can be done elsewhere.

Both of these problems can be solved by creating web applications using web technologies such as HTML5, CSS, and JavaScript programming, that work across all platforms (Corral & Sillitti 2012). The improvements in cloud computing and storage mean that both computationally intensive data analysis and 3D rendering can take place in the cloud, and all the user needs to do is to display the results in his web browser. Due to these reasons, web applications have gathered an increasing interest. Since most people nowadays have access to the Internet, having a browser with JavaScript support is typically more than enough to support the use of web applications.

IIoT also opens new areas for data visualization. The increasing "self-awareness" of devices and their "understanding" of how they relate to other devices in the network can be used to create new information that has been previously impossible. For example, visualizing the data flow between devices as they communicate with each other. An example of communication between devices could be a production line in which device #1 tells device #2 that it is starting to malfunction, and therefore device #2 makes automatically a decision to decrease the material flow towards device #1, and instead reroute the materials to device #3.

Another important impact of the IIoT on visualization, as a result of the increasing amount of collected data, is that apart from the need for better techniques and methods for data analysis, the role of interaction between people and visual representations will be even more significant than before. These are discussed in the next section.

2.4.6 Enhancing data visualization via interactive techniques

Interaction plays a huge role in achieving great data visualizations and its importance will continuously grow, as a result of the increasing amount of collected data due to the IIoT. As stated by Ware (2012, p.345), displaying a static picture or a three-dimensional virtual environment which allows the user to simply walk through and "inspect like a museum full of statues" is not an example of good visualization. According to him, good visualization requires that the user is able to also interact with it in ways that present more information when needed, hide the information when not needed and accept commands and requests from the user that aid the thinking process. Dix et al. (2004, p.746) also emphasizes that through an interactive visual representation the user can obtain a deeper understanding of the presented data and discover new patterns and features that would very likely be left unnoticed if static representation was used. Some of the most modern computer interaction techniques for data visualization are described below.

Selection

Selection is one of the most basic, most fundamental and most commonly used user interactions found in computers nowadays. As stated by Yi, ah Kang & Stasko (2007), selection allows users to mark an object of interest so that it can be easily tracked. Highlighting the selected components could, therefore, be a good idea firstly, because it notifies the user that the selection was performed successfully and secondly, because it tells the user exactly what was selected. In rapidly evolving environments with many data items selection can be very useful since otherwise changes in visual representations may be hard to follow by the user. Yi & ah Kang (2007) note that selection often precedes and is coupled with other interaction techniques, rather than being a standalone interaction technique. This enriches the exploration of data and discovery of information. (Ware 2012, p.347)

A selection is typically executed using a mouse or a similar input device by placing the pointer above the object of interest and clicking. Depending on the purpose, the user might want to select multiple objects. A commonly adopted way for multiple selection on desktops is pressing a key on the keyboard (CTRL) and clicking on the objects of interest while holding down the key.

Hover queries

Displaying information upon hovering is another rather commonly used user-interaction method. This method is typically implemented using tooltips or other data displays that appear when the user points to an area of interest in the visualization. (Soegaard & Dam 2012) The data displays are generally boxes displaying some additional information of an object. It is not necessary that all the displayed objects support a hover query. Thus, nothing happens when hovering the mouse pointer over an object that does not support this functionality. However, if the object does support hovering queries, the data display would usually appear right next to the mouse pointer.

Typically, the user is required to hold the mouse pointer over a part of the visualization for a short period of time before the hover query is activated and a data display appears. The reason behind this is to keep the visualization clear, as well as less computationally intensive.

As stated in Soegaard & Dam (2012), an advantage of hovering queries is that this type of interactions are effortless and easy to discover.

Zoom, pan and rotate

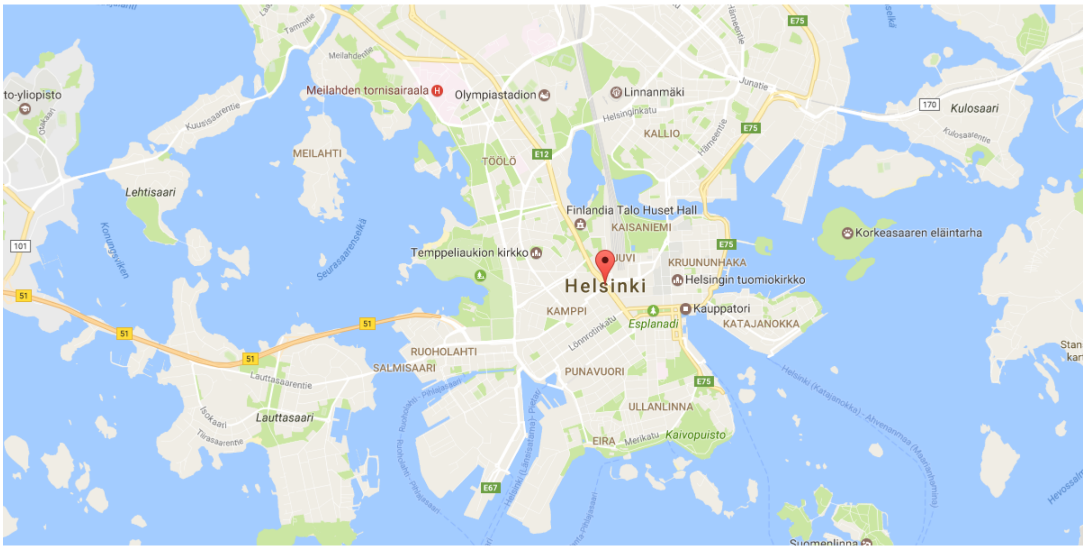
One of the modern ways to visualize virtual environments is in three dimensional space, in which the user needs to be able to interact with the visualization or rather with the camera. As stated by Khan et al. (2005), when the user input comes from a 2D device such as a mouse, metaphors are needed to assist the user, of which a very common one is the cinematic camera model. It enables the user to interact with the 3D model by zooming, panning and rotating the viewpoint.

A famous mantra developed by Shneiderman (1996) is "overview first, zoom and filter, then details on demand." According to Spence (2014, p.140), zooming can be divided into two subclasses: geometric zoom and semantic zoom. Geometric zoom is the simpler of the two in which zooming-in results in merely a magnified view of a fraction of the scene, upon which the zoom-in action was performed. An example of geometric zoom is zooming-in with a phone camera.

The second type, semantic zoom, is the more interesting of the two. As stated by Spence (2014, p.141), applying a semantics zoom on objects or data is not constrained to changing only their size, as is the case in geometric zoom. Other changes, such as changes of color, shape, texture, and maybe most importantly presence, are also allowed. Such changes can, and usually, lead to an entirely new structure of the represented data with the main purpose of displaying the most useful data to the user in a confined display space. A good example of a semantics zoom is shown in Figure 23, in which zooming-in shows a reduced geographical area but more details of local places and their names. Therefore, zooming is suitable for exploring different levels of detail.

Panning refers to the movement of the camera in parallel to the current view plane (Autodesk n.d.) and is useful for positioning the model around the two dimensional

(a) Starting image



(b) Resulting image after a semantics zoom-in applied

Figure 23: A semantic zoom. Part (a) shows the starting point. Part (b) is the result after zoom-in applied.

display. On desktop computers panning is typically executed by first selecting the panning tool, then clicking down and holding the left mouse button, and moving in the desired direction along the screen.

Rotation, on the other hand, is very useful for getting a different perspective of the 3D model and for revealing features seen from that specific view point. This is done by changing the view angle and camera position from which the user looks at the 3D model. More scientifically described, rotation rotates the viewed scene around the axis of the camera.

Filtering

According to Spence (2014, p.67), filtering can have a significant impact on the ease of acquiring insights from data. The filtering interaction technique (Yi & ah Kang 2007) provides users with the ability to specify the set of data items which are shown in the visual representation. This is done by allowing the user to specify a range of filtering criteria and according to it only the data items that satisfy the criteria are visualized, whilst the rest of the data items are deemed irrelevant and are hidden from the visualization, i.e. filtered. These irrelevant data items are, however, not deleted and the actual data is not changed in any way. Thus, all hidden data is recovered upon a reset of the filtering conditions. (Yi & ah Kang 2007) Soegaard & Dam (2012) state that filtering can be very useful when dealing with large datasets (Soegaard & Dam 2012). An important note by Spence (2014, p.67), is that a user must be very careful when deeming some data as irrelevant and filtering it out, as this could lead to hiding important information and have a negative impact.

According to Mazza (2009, p.116), data filtering that occurs in the preprocessing phase of visualization can be used for two main purposes:

1. to remove data items and attributes from the dataset which are not needed for the visual representation, due to them being both irrelevant and not required.

2. to aid the analysis focused on certain parts of the dataset, such as investigating how including or excluding some attributes affect the visual representation.

2.4.7 Modern process visualization techniques

As stated by Ware (2012, p.5), high interactivity in visual representations is nowadays essential in order to understand the massive amounts of increasingly complex data gathered. A modern method widely used to improve visualization and to bring computer interaction closer to our physical reality is the interaction in three dimensional space. One of the most important arguments for the usage of a third dimension in visual representations of data is that it enables users to manipulate 3D models in ways that present different vantage points, which leads to a better and quicker understanding of the information. Three of the most fundamental interactions with a 3D model - zoom, pan and rotate - were presented in Section 2.4.6. As noted by Mazza (2009, p.30-31), 3D visual representation brings a lot to the table especially when it is used to represent a moving object or when the data represented has a 3D spatial component.

Process data itself in manufacturing facilities can be presented much more efficiently in 3D models compared to traditional flat models, exactly due to the presence of a third dimension. The third dimension enables the division of process data into different hierarchical levels with each one displaying only data relevant to that level. Navigating between levels can be implemented using a "drilling" method, such as zooming. As a result, visualizing process data in 3D models is an excellent way to cope with the huge amounts of data brought by the IIoT.

As always, there are also some valid arguments against the usage of a third dimension when visualizing data. One of the strongest one is that 3D visual representations increase the cognitive load, requiring more mental effort from the user to correctly interpret the represented data. There are also some minor arguments, as the one noted by Mazza (2009, p.29), that when using three dimensional visualization, occlusion is an important thing to consider. It refers to the possibility of having some graphical elements "hidden" from the user because they are positioned behind other graphical elements that are in the front in the 3D model. Of course, this is solvable by rotating the object of interest, however, the user would need to go one step further to find the information, which may quite often not be done if not knowing that additional information exists.

There are several ways of achieving the interaction with computers in three dimensional space. The most modern techniques are that of virtual reality (VR) and augmented reality (AR). The difference between virtual reality and augmented reality is that in VR the user is entirely immersed in a virtual three dimensional environment, whilst in AR the user experiences the normal physical world with overlaid virtual objects in it. Both VR and AR are achieved via the usage of special glasses. In VR virtual glasses mounted on the user's head project the virtual reality and block him from seeing the physical world around him. AR glasses, on the other hand, do not block the user from seeing the physical world but project objects on top of it. The user can thus explore the virtual reality by walking around in the physical world and can manipulate objects in the virtual reality using specifically dedicated inputed devices, such as gloves.

A simpler technique, which is already well-established, is to create the sense of three spatial dimensions on a two dimensional computer screen. This is achieved using as variety of sources called depth cues, which the human brain associates with three dimensional space. An example is a category called pictorial depth cues which uses two dimensional sources of information that are interpreted as three dimensional by the human visual system. Some cues that belong to this category are occlusion, shading, relative sizes and shadows. (Pfautz 2002)

This Master's thesis is focused on the last of the aforementioned methods. The implementation process of integrating a visualization component into ABB's PIMS solutions is covered in Section 3.

3 Implementation methodology

The purpose of this section is to cover the developed implementation methodology. The methodology was applied for determining the two most suitable 3D visualization toolkits available at the time for developing the proof of concept and for evaluating them throughout the implementation. The intention behind the evaluation was to provide a better understanding of the two toolkits and to guide the choice of a toolkit with which to continue further development beyond the proof of concept implemented in this Master's thesis. Additionally, the market readiness for the concept was evaluated and some remarks were made.

The methodology consisted of the following steps:

1. Determine the two best 3D visualization tools to use for developing the proof of concept:
   (a) Define the requirements originating from existing software.
   (b) Execute a market research on available 3D visualization tools and create the initial list.
   (c) Filter out the unsuitable options from the initial list by evaluating each tool against the requirements.
2. Evaluation principles for selected 3D visualization tools
3. Evaluation of market maturity
4. Evaluation remarks

The following subsections describe the execution of this methodology.

3.1 Determining the two most suitable 3D visualization tools

The first steps of the methodology were aimed to quickly and efficiently yield the two most suitable 3D visualization tools which are to be used for the creation of the proof of concept.

3.1.1 Define the requirements

The starting point of the implementation process was to cover the fundamental requirements that had to be met by the 3D visualization tools. The resulting set of requirements was used to filter out the unsuitable options from the initial set of 3D visualization tools in order to yield the two best tools to use for developing the proof of concept. The two groups of requirements identified for this project are discussed below.

Technical requirements

The first set of requirements that had to be carefully considered were the technical requirements imposed on the 3D visualization tools by the software into which the 3D visualization components were to be integrated. The resulting list, for ABB's software specifically, was the following:

- The tools should support the development of 3D visual representations for use in both a desktop environment, as well as in web environment.
- The software development kits (SDKs) used for developing 3D visualizations for use in desktop applications should be either written in C# or provide a C# API. The reason behind this is because ABB's desktop PIMS solution, Vtrin, is written in C#.
- The SDKs used for developing 3D visualizations for use in web applications should support JavaScript programming and HTML5.
- Technical support should be offered along with the tools.

Core functionality requirements

The second set of requirements that were considered were those of core functionalities. This set of requirements determine the key functionalities without which the system will be completely useless. For this specific case the following were identified:

- The tools should support importing and visualizing 3D CAD models. The range of 3D CAD formats supported by the tools should be as broad as possible but at least the most common formats should be supported.
- The tools should offer basic user interaction with the loaded 3D models, such as zoom, pan and rotate.
- The tools should enable the user to create custom operators/interactions and to modify existing ones. Examples of such interactions are selection, hovering queries and filtering.

3.1.2 Market research and filtering process of 3D visualization tools

The next step after determining the requirements was to conduct a market research on the available commercial and open source 3D visualization tools. The research yielded the following initial list: SAP 3D Visual Enterprise, Cortona3D, HOOPS Visualize, Geoweb3D, nGrain, Open Inventor, OGRE, and VTK.

One of the initial tools that was supposed to be used was the SAP 3D Visual Enterprise. However, after some discussions with SAP it turned out that this product is not yet available for licensing for use with 3rd party software. Therefore, the product dropped out from the list prior to running the requirements filter discussed in the previous section. In order to find the most suitable candidates for achieving the required goals, the remaining options were run through the requirements filter.

The results were that some of the interfaces to the SDKs were written in C++, such as Geoweb3D, OGRE and VTK, and wrappers would have been required to allow for programming in C#. Therefore, these tools were filtered out. Others did not support web deployment —nGrain— and were dropped out as well. Finally, some offered independent products but integration with ABB's PIMS solution would have not worked well as their SDKs have not been updated for many years and provided no technical support (Cortona3D). Therefore, this option was also filtered out. As a result, the two most promising products that fit all the requirements and were selected for the purpose of this Master's thesis were Open Inventor by FEI and HOOPS Platform by Dassault Systemes. Both of these companies provided a free-of-charge trial-period of their tools for developing the proof of concept. The two tools are briefly introduced below.

Open Inventor

FEI markets Open Inventor as a "high-performance 3D software development toolkit (SDK) for professional applications in Medical, CAD & Engineering, Oil & Gas and Mining." It provides an object-oriented application programming interface (API) which can be used for the integration into existing applications. Furthermore, Open Inventor supports development in C++, C# or Java via a fully native API layer. (FEI 2017*a*)

Apart from providing 3D rendering on local machines, Open Inventor can also be used in web-based applications to provide rich interaction and visualization capabilities remotely. This is achieved with the help of the Open Inventor RemoteViz service. The rendering of the 3D model is done entirely on the server-side and only rendered images are sent back to the client, which are then visualized in the web browser. Upon user interaction with the image, a request is sent back to the server, which renders each frame and sends back the result to the client in the form of an image. Therefore, the client simply needs a web browser which is able to display images and which supports JavaScript programming.

Additionally, the Open Inventor product team provides technical support for various environments in case any issues are encountered during the integration and deployment phases. (FEI 2017*a*) Open Inventor supports many CAD file formats which can be loaded by obtaining the appropriate license from FEI. These are discussed in Section 3.4.

HOOPS

HOOPS is a commercial 3D graphics API specifically targeting the engineering industry. The HOOPS product family consists of four toolkits: HOOPS Visualize, HOOPS Communicator, HOOPS Exchange, and HOOPS Publish. (Tech3DSoft 2017) Only the first three are briefly described below as they are of interest to this thesis.

HOOPS Visualize is the standard graphics engine used for developing high-performance applications for both desktop and mobile use. It supports C, C++, C# and Objective-C programming languages. (Tech3DSoft 2017)

HOOPS Communicator is a powerful toolkit that enables the development of advanced 3D enriched web applications. It is built on top of the HOOPS Visualize, HOOPS Exchange and HOOPS Publish products, and supports both client-side and server-side rendering capabilities. (Tech3DSoft 2017)

Similarly to Open Inventor, when the user interacts with the model and the rendering is set to server-side rendering, each frame is rendered on the web server and the resulting image is streamed back to the client. The resulting benefits are that the client does not need to support WebGL nor have 3D hardware.

Additionally, HOOPS Communicator provides an option for client-side rendering, in which the client downloads the model file from the web server and displays it using WebGL. (Tech3DSoft 2017)

HOOPS Exchange is a "set of high performance software libraries designed to provide software developers with the ability to read and write popular 3D formats from within their application". (Tech3DSoft 2017) With the help of HOOPS Exchange a number of popular 3D CAD file formats can be used in HOOPS Visualize and HOOPS Communicator. These are discussed in Section 3.4

3.2 Evaluation principles for selected 3D visualization tools

The integration and development process of the proof of concept was initiated once the two tools were selected. During this entire process the selected tools were evaluated against the following criteria in order to compare them to each other and to provide a solid basis for choosing one toolkit for further development after the completion of the Master's thesis:

- Ease of installation
- Content of installation package
- Documentation usefulness
- Quality of technical support
- Out of the box functionalities
- Toolkits' desktop architecture and platform support
- Toolkits' web architecture
- Licensing costs

Each one of these evaluation points are discussed in detail below:

Ease of installation, content of installation package and evaluation period

The installation packages of the SDKs of both Open Inventor and HOOPS were well-made and the installation processes were quite straightforward. Each one of the installations included demonstrations and examples that covered the most important topics and functionalities of the toolkits. Running the demos worked out of the box for both tools with the exception of having to manually handle licensing by inserting a license string in the correct location. A free evaluation license was provided by both companies for the purpose of developing the proof of concept.

In addition to the demos of basic functionalities, the installation of HOOPS Visualize came with several sample sandbox applications to demonstrate its operation with various graphical user interface (GUI) toolkits. The sandboxes proved to be a good starting point to load 3D models, interact with them via the standard operators, explore the model's scene graph via the segment browser, and run user-written code. The WPF Sandbox is shown in Figure 24. Open Inventor too provides a viewer called "IvTune", using which the user can interact with loaded 3D models, explore the scene graphs and even alter them during run-time. The IvTune editor can also be opened in any environment where Open Inventor is running, for example in the integrated environment with ABB's software, as shown in Figure 25.

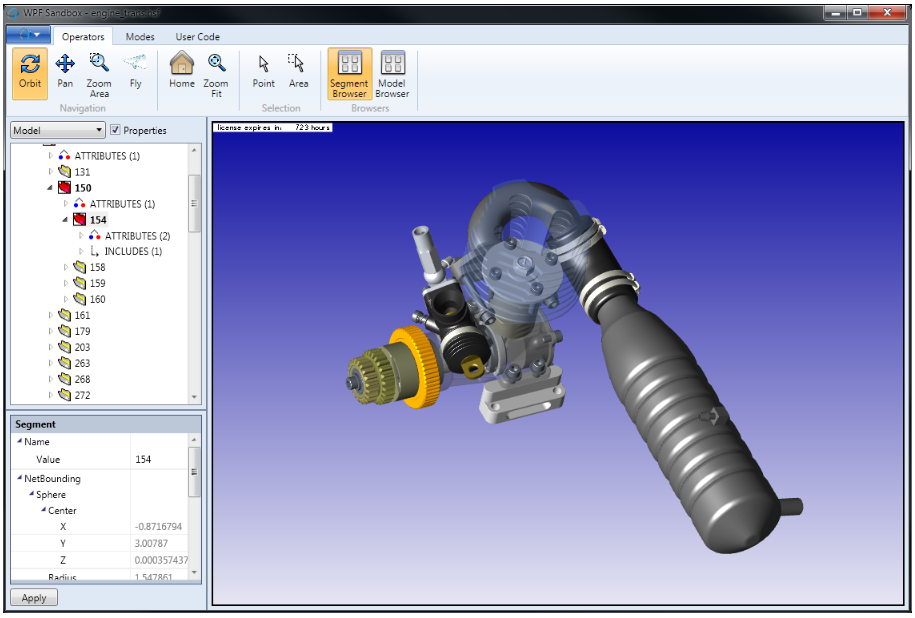


Figure 24: Exploring a scene graph of an example 3D model using the WPF Sandbox that came with HOOPS Visualize.

In Open Inventor, the necessary files (RemoteViz) for developing 3D visual representations for use in a web environment were included in the basic installation file. Deploying 3D web visualizations required only a modification in the license file. In HOOPS, on the other hand, a separate installation of HOOPS Communicator was required for the purpose, which is an independent product and is marketed separately

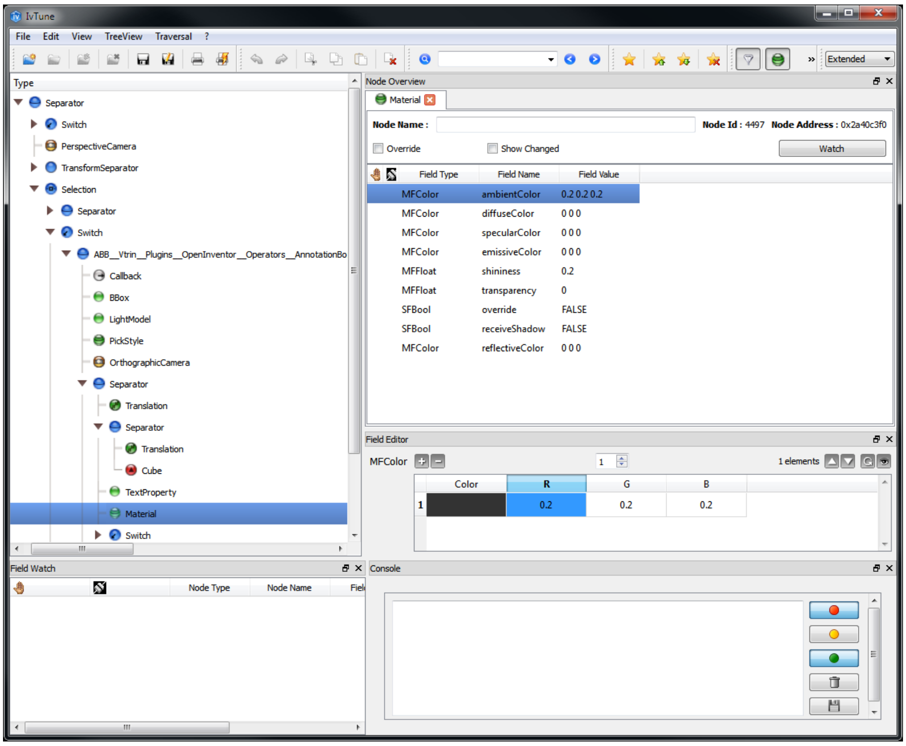


Figure 25: Open Inventor's IvTune window opened from within the integrated component into ABB's Vtrin.

from HOOPS Visualize.

Documentation, technical support and product trainings

Both tools provide extensive documentations to get developers started. The documentations include overviews of the tools, such as technical overview, supported file formats, and troubleshooting, programming guides, API references and explanations of the demo codes. The documentations come with the installation packages for offline use but can also be found online. The online documentations offer a search action.

Open Inventor's programming guide comprises of two books called Open Inventor Mentor that come in two volumes. The first volume covers the core of Open Inventor. The purpose of the second volume is to provide a user's guide for extensions modules for Open Inventor. The examples provided in the books are written only in C++. HOOPS documentation, on the other hand, provides examples written in C++ and C#.

Both companies provided an excellent technical support for each of the used products during the entire evaluation period. Close collaboration was maintained with the companies throughout the integration process; they were actively participating in meetings, providing advice, offering solutions, and wanted to be kept up to date with the progress of the Master's thesis. Additionally, the two companies provide and organize general trainings, as well as personalized trainings according to the customer's needs.

Out of the box functionalities

In addition from providing rendering capabilities each one of the toolkits comes with a set of pre-built, standard operators that enable the user to interact with the scene graph through panning, zooming and rotating. Furthermore, the toolkits offer the possibility to subclass the standard operators in order to create custom operators according to the user's needs. The purpose of the operators is to process different input events, such as mouse, keyboard and touch events. Thus, more sophisticated user interactions, such as hovering queries and filtering, can be implemented separately. In both toolkits, callback functions enable the change of the scene graphs during runtime. Both tools are also able to import a wide range of 3D CAD formats.

Toolkit desktop architecture and platform support

Open Inventor is cross-platform solution that works on Windows, Linux and mac OS. As can be seen from Figure 26, Open Inventor's foundation is based on OpenGL and UNIX. On top of that the Open Inventor toolkit represents an object-oriented application policy that handles the database of the scene and the manipulators for interacting with the scene, as well as provides a user interface to OpenGL programs. The scene database's structure is a hierarchical tree consisting of nodes. (FEI 2017*d*)

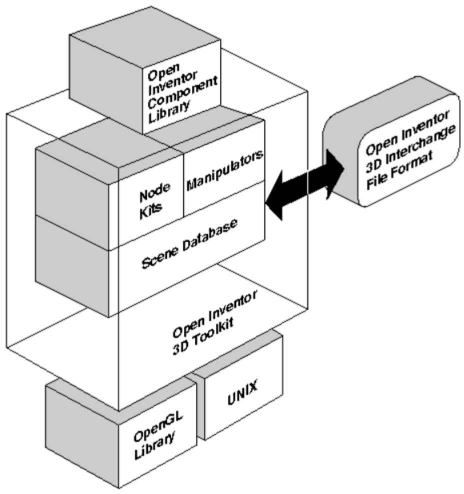


Figure 26: Open Inventor architecture. (FEI 2017*d*)

HOOPS Visualize is a cross-platform solution that works on Windows, Linux and mac OS, and uses optimized OpenGL and DirectX drivers to exploit the available graphics hardware. At the core of HOOPS Visualize is the graphics kernel, called Core Graphics, which is a scene-graph technology focused specifically on engineering. The graphics database, called the scene graph, is a data structure in the form of a hierarchical tree comprising of nodes. On top of the graphics kernel layer lies the software components layer called "Sprockets". The sprockets layer includes integrations of complementary components used in engineering software that allow users to for example import CAD models and also provides standard operators for manipulating 3D models. These can be seen from Figure 27. (TechSoft3D 2017*b*)

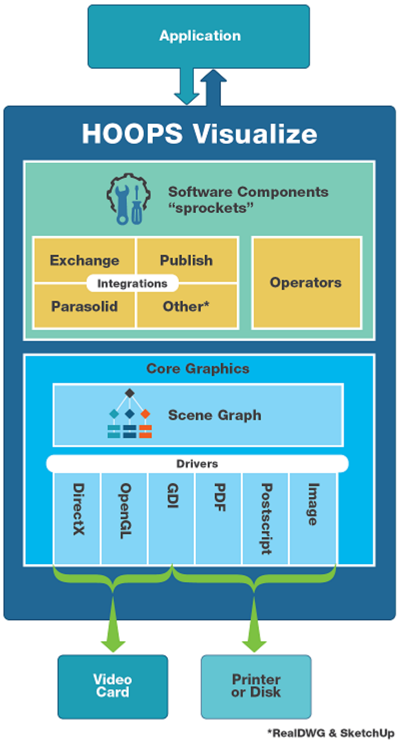


Figure 27: HOOPS Visualize architecture. (TechSoft3D 2017*b*)

Toolkit web architecture

On a general level, both of the tools require a service to be running on the host machine which is responsible for the rendering, as well as JavaScript code running on the client that interprets the received data and takes care of the visualization in the web browser.

In Open Inventor, this is achieved using the RemoteViz library. It consists of the RemoteViz rendering service that runs on the server side, as well as a JavaScript library that runs on the client side. The RemoteViz rendering service is responsible for data access, computing and 3D rendering. It enables the reuse of the existing Open Inventor 3D visualization code used for standalone applications (e.g. the C# code developed for use with Vtrin) by providing a wrapper. It also initiates a web server which is responsible for interpreting user interactions, rendering the new scene and sending it to the client. (FEI 2017*c*)

The client is responsible for the user interface and image display. Therefore, the purpose of the JavaScript running on the client-side (web browser) is to transfer user interactions and to refresh the display. In the latest version of Open Inventor a support for the H.264 video codec has been implemented in RemoteViz which uses an advanced compression method. As a result, the bandwidth usage between the clients and the service is reduced by 30% in comparison to JPEG encoding for the same image quality. The RemoteViz architecture is illustrated in Figure 28. (FEI 2017*c*)

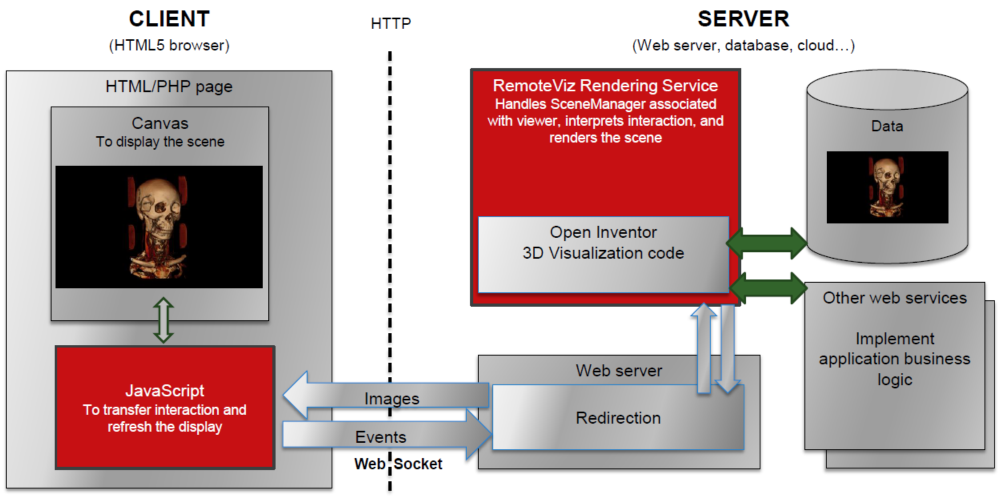


Figure 28: The RemoteViz architecture. (FEI 2017*a*)

The technical architecture of HOOPS Communicator, on the other hand, is shown in Figure 29. In a similar way to Open Inventor's RemoteViz, HOOPS Communicator consists of a server-resident file processor, called HOOPS Converter, and a JavaScript viewer, called HOOPS Web Viewer, that runs on the client-side in a web browser. The HOOPS Converter is able to read over 20 different file formats, extracts the content and produces the necessary outcome for viewing with HOOPS Web Viewer, which is also responsible for the interaction. The underlying difference of HOOPS Communicator in comparison to Open Inventor's RemoteViz is that HOOPS Web Viewer is also capable of doing the rendering itself using WebGL, in addition to being able to display streamed images rendered by the server — server-side rendering (SSR). (Tech3DSoft 2017)

Licensing costs

As discussed previously, a free evaluation license was provided by both the Open Inventor team and the HOOPS team for the duration of the Master's thesis implementation. Nonetheless, as both tools are commercially marketed products their use beyond the scope of the Master's thesis would require an agreement on the licensing terms and licensing costs. The negotiation of these, however, is beyond the scope of the thesis which merely aims at laying a solid basis for choosing one toolkit for further development after the completion of the Master's thesis. The licensing costs, are, therefore, not discussed in more detail.

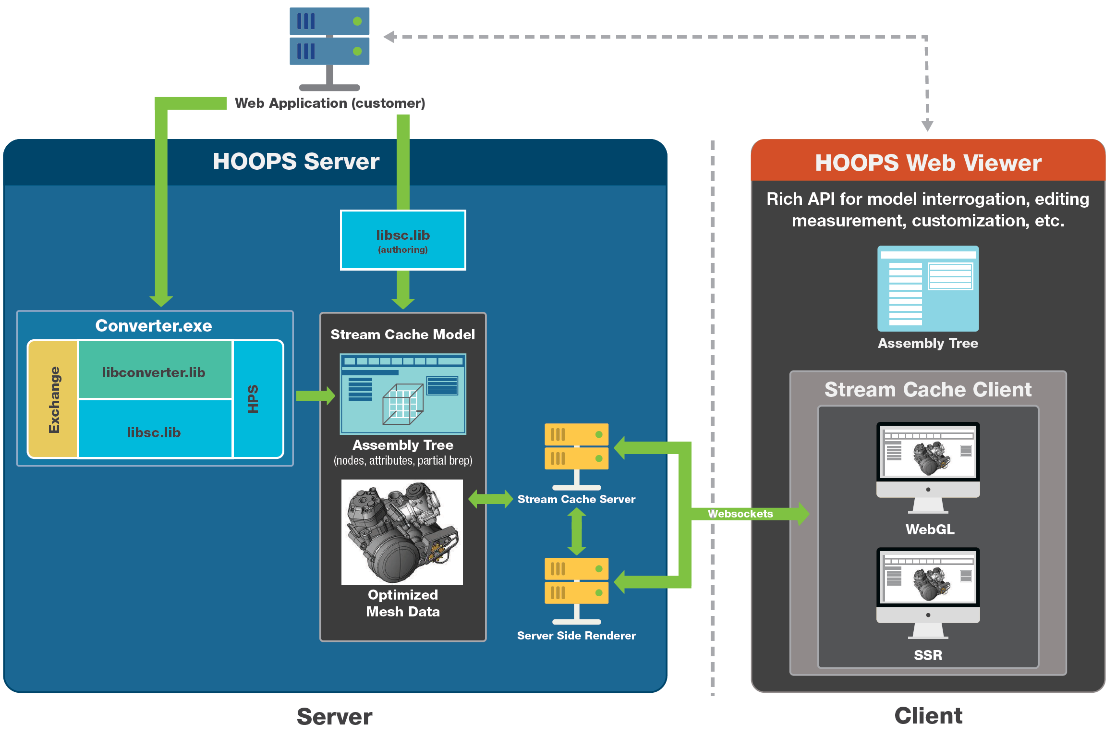


Figure 29: The architectural diagram of HOOPS Communicator.(Tech3DSoft 2017)

3.3 Evaluation of market maturity

The maturity of the market and its willingness and readiness to adopt IIoT solutions were also evaluated during the implementation phase. This was done by applying the following criteria:

- Availability of 3D models of manufacturing facilities.
- Manufacturers' (customers') readiness and willingness to jump on board and supply 3D models and data for creating the proof of concept.
- Availability of readily implemented functionalities in 3D toolkits aimed at manufacturing industries.
- Readiness and enthusiasm of 3D toolkit suppliers to help develop the proof of concept.

Availability of 3D models and willingness to partner

The following list shows the different groups into which customers can be categorized with respect to their attitude towards the concept.

- No interest in the concept; does not see a business case. (concept has no market potential)

- No readily available 3D models; shows interest. (concept has future market potential)
- Available 3D models but shows hesitation on whether to partner with ABB to develop the proof of concept. (concept has future market potential)
- Immediate readiness to partner and to develop the concept. (current market potential)

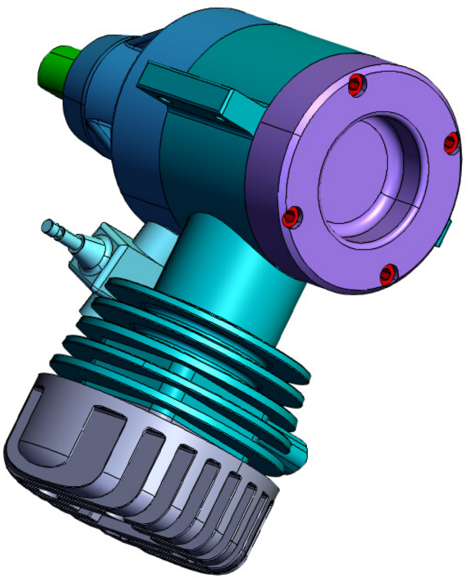
Each group was also assigned an interpretation of the market potential for the concept which can belong to one of three categories: no market potential; current market potential; future market potential. The "no market potential" group means that the concept has no current nor near-future market potential for customers belonging to this group. Therefore, at the current moment it is irrational to further pursue these customers to partner with ABB. Similarly, the "current market potential" and "future market potential" groups mean that the concept has current market potential or future market potential, respectively, to customers that belong to that group. It is therefore essential to continue to pursue customers belonging to these groups to partner with ABB for the future development of the concept.

During the implementation phase of the Master's thesis a number of customers were approached and presented with the concept, and were asked whether they are interested in partnering and developing it around their 3D models and process data. It became apparent that most of them were not ready for the shift.

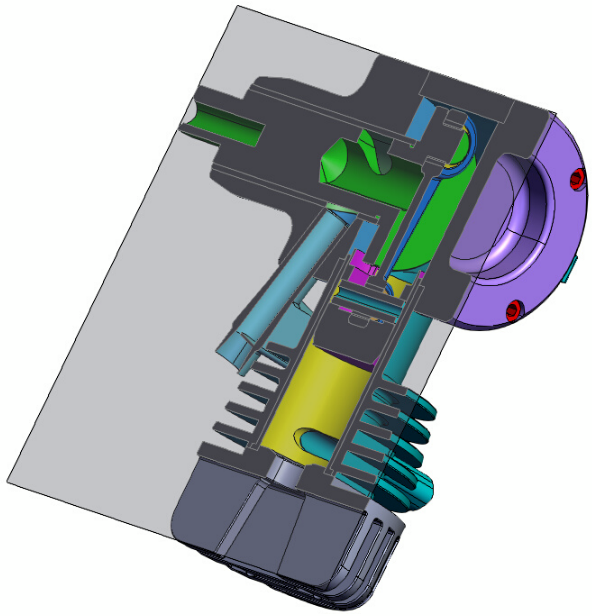
The first customer asked from the manufacturing industry did not have 3D models of his equipment but showed interest in the concept. As a result, this customer was classified as a future market potential. The second customer asked belongs to the discrete manufacturing industry. This customer did not immediately turn down the offer due to the lack of 3D models but instead, showed some hesitation on whether to partner with ABB on this journey and to share the 3D models and data. This was interpreted as the customer not currently seeing use of the concept in his production. Therefore, this customer as well was classified as a future market potential. Finally, the third customer asked from the process manufacturing industry showed immediate interest and readiness to share 3D models and data for the development of the concept. Therefore, this customer was classified as the current market potential.

The state of the available 3D toolkits

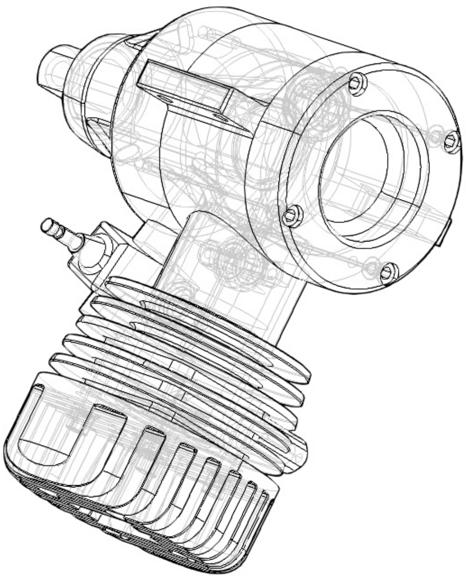
Both of the selected toolkits provide general functionalities that are important for interacting with 3D models for any application. Additionally, the toolkits allow users to program operators and manipulators of their own, which is of great importance for the future development of the concept. During the implementation phase it was observed that Open Inventor supplies more general level functionalities that try to cover many different application areas. Open Inventor provides a strong core technology that has been developed over the course of 30 years and has a major focus on improving performance. HOOPS, on the other hand, though also being suitable for a range of different applications, seemed to be more focused on engineering applications. This can be seen by the additional functionalities that have been implemented which are quite suitable for engineering purposes. Examples of such functionalities, shown in Figure 30, are cutting planes – which allow to cut away parts of a scene and show the inner pieces of an model, exposing details that are otherwise obscured; hidden lines view – displaying all edges of the model; exploded view – showing the components separated from each other; and overlay – using transparency to reveal inner parts of the model.



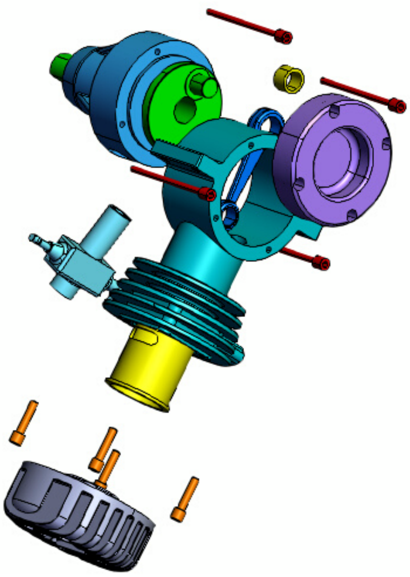
(a) Normal view of the 3D model



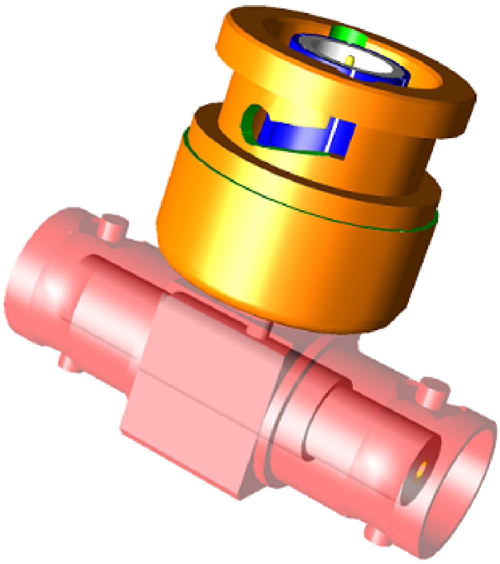
(b) View with a cutting plane applied half-way through the 3D model



(c) Hidden lines view



(d) Exploded view



(e) An overlaid 3D model

Figure 30: A variety of implemented HOOPS functionalities suitable for manufacturing industries. [models from HOOPS]

As previously discussed, the technical support provided by both Open Inventor and HOOPS teams were excellent throughout the entire implementation phase. Each of the two companies showed great interest and enthusiasm to continue cooperating with ABB beyond the scope of the Master's thesis and to develop the concept for commercial use. Furthermore, research showed currently very little to no usage of 3D visualization for process data in manufacturing facilities. Combing these observations with the trouble of obtaining 3D models from ABB's partners in the manufacturing industry, it was concluded that 3D visualization of process data in manufacturing is a rather new application area and new business case for companies developing the 3D toolkits. The state of the available 3D visualization toolkits, though not focused for usage in manufacturing industries alone, provide a great base for further development in the area. The companies developing these toolkits continuously evolve and align their businesses to meet the needs of new customers.

3.4 Evaluation remarks - the lack of 3D CAD models

Upon questioning customers to take part of the implementation phase of the Master's thesis, it became apparent that very few of them have readily available 3D CAD models of their manufacturing facilities and production machines. Therefore, in the scenario that ABB decides to proceed developing the concept it is likely needed for them to supply the 3D CAD models as a part of the package. The two options for ABB, in such case, are either for them to outsource the job for creating the 3D CAD models or to be able to create the 3D CAD models internally.

There are a many important questions that need to be answered before choosing either option. Some of these are:

- What are the applications for which the CAD models are needed?
- What type of data needs to be displayed in the applications?
- Which CAD tools can handle such data?
- What file formats need to be supported?
- Are there people within the company with the required set of skills for the job?
- Can the work be outsourced?
- How big is the set of customers that are likely to adopt the concept in the short term and what is the expected growth rate?
- What are the short term and long term prices of either solution?

Inherently, some of these questions are more difficult to answer than others and the answers are more uncertain. For example, it is essential to know the set of interested customers, and an approximate answer can be obtained via surveys, however, nothing prevents them from dropping out from this set at a later stage.

The rest of this section presents the supported CAD file formats by Open Inventor and HOOPS Exchange, as shown in Tables 1 and 2, respectively, and briefly lists some tools for creating 3D CAD models specifically for plant and factory designs.

Table 1: CAD formats supported by Open Inventor (FEI 2017*b*)

CAD format	**Version**
AutoCAD (.dwg)	From v2.5 up to 2013
CATIA V5 (.catpart, .catproduct)	From R7 to R23
CATIA V6 (.3dxml)	From R2010x to R2013x
Creo (.asm, .prt, .xas, .xpr)	From Pro/E 2000i to Creo Parametric 2.0
IGES (.iges, .igs)	Until 5.3
JT (.jt)	Supports tessellated Jt 3d files and B-Rep. Up to 9.5
CATIA V6 (.3dxml)	From R2010x to R2013x
Parasolid (.xmt, .x_t, .x_b)	From v7 to v26
Solid Edge (.par, .asm, .psm, .pwd)	up to ST6
SolidWorks (.sldasm, .sldpart)	from version 1999 to 2014
STEP (.step, .stp, .stp.Z)	AP203(Edition 1 and 2), AP214 (up to Edition 3), AP242 (Edition pre-DIS)
VDA (.vda)	
Unigraphics (Ug)	

Table 2: CAD formats supported by HOOPS Exchange (TechSoft3D 2017*a*)

CAD format	Version
ACIS (.sat, .sab)	Up to v26.0
AutoCAD (.dwg)	From v2.5 up to 2013
Autodesk Inventor (.iam, .ipt)	Up to 2017
CATIA V4 (.dlv, .exp, .model, .session)	Up to 4.2.5
CATIA V5 (.catpart, .catproduct)	Up to V5-6 R2016 (R26)
CATIA V5 (.3dxml)	Up to V5-6 R2016 (R26)
CATIA V6 (.3dxml)	Up to 2013x
Creo (.asm, .neu, .prt, .xas, .xpr)	Pro/Engineer 19.0 to Creo 3.0
I-deas (.mf1, .arc, .unv, .pkg)	Up to 13.x (NX 5), NX I-deas 6
IFC (.ifc, .ifczip)	IFC2x Editions 2, 3 and 4
IGES (.igs, .iges)	5.1, 5.2, 5.3
JT (.jt)	Up to v10.0
Parasolid (.xmt, .x_t, .x_b)	Up to v28.1
Rhino3D (.3dm)	v4 and v5
Solid Edge (.par, .asm, .psm, .pwd)	v19 - 20, ST - ST9
SolidWorks (.sldasm, .sldpart)	from version 1997 to 2017
STEP (.step, .stp, .stp.Z)	AP203(Edition 1 and 2), AP214, AP242
Stereo Lithography (.stl)	All versions
U3D (.u3d)	ECMA-363 (1^{st}, 2^{nd} and 3^{rd} versions)
Unigraphics-NX (.prt)	v11.0 to NX 11.0
VDA-FS (.vda)	v1.0 and v2.0
VRML (.wrl, .vrml)	v1.0 and v2.0

A list of CAD applications targeted specifically at plant design and factory design that might be worth investigating, in case ABB decides to create the 3D models themselves, are:

- MPDS4 by CAD-Schroer
- Everything3D by Aveva
- AutoCAD and Inventor by AutoDesk

4 Integration and results

The chosen 3D visualization toolkits, discussed in Section 3.1.2, were integrated on top of two ABB PIMS solutions that work in different environments. The first is called Vtrin and is a locally installed desktop application used for visualizing real-time information of process data. The second is a web framework whose purpose is to display similar content as is displayed in Vtrin but in a web browser. The integration of the 3D visualization toolkits into each one of these environments are covered briefly in Sections 4.1 and 4.2, respectively.

4.1 Case example: Vtrin

This section describes the integration process of the 3D toolkits into the Vtrin UI and presents the results. At first, a brief overview of the Vtrin UI is given in Section 4.1.1, which also discussed the important parts for the implementation. Section 4.1.2 describes the common steps needed for the creation and integration of a plug-in for use with the Vtrin UI. Following these, are more detailed descriptions of the integration of Open Inventor and HOOPS Visualize, in Sections 4.1.3 and 4.1.4, respectively.

4.1.1 Overview

The starting point with the Vtrin UI is shown in Figure 31.

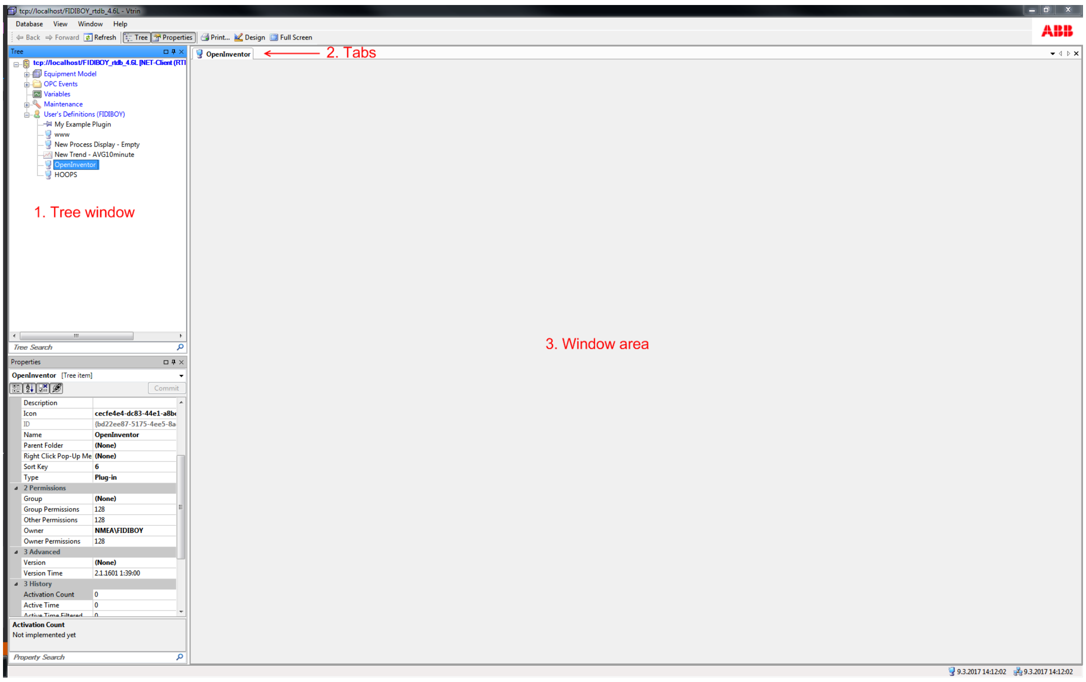


Figure 31: The starting point with Vtrin UI.

The three most important parts of the Vtrin UI for this thesis are marked with numbers from one to three in Figure 31. Firstly, the tree window (1.) can be seen in the top left corner of the figure in this simple setup of the application. It shows the system's windows (which are also known as charts) in a hierarchical tree structure. The part of interest to this thesis is the User's Definitions in which, as the name suggests, the user is allowed to define and construct different kinds of displays according to his interests. A user defined display can either be one of the built-in basic types, such as a list or a trend, or it can be a plug-in that is separately integrated into the application. For the purpose of this work, it was decided to create two plug-ins that use the chosen 3D toolkits (Section 3.1.2), which can be integrated into the Vtrin UI using the aforementioned method.

Upon the selection of a component from the tree window, the display should open as a tab. The positions of the tabs are shown by the second marking (2.) in Figure 31. It is possible to have multiple displays loaded into different tabs. The currently selected tab presents its contents in the Window area whose location is indicated by the third marking (3.) in Figure 31.

4.1.2 Vtrin plug-in creation and integration

The first step of the integration process was to create a plug-in that is loaded in the Vtrin UI, as described in the previous section. Upon the start of the Vtrin application, the program checks a specific folder in the installation path for the existence of files with a .dll extension, which is the format that the plug-ins need to be in order to be found and read. Therefore, the output path of the plug-in project needs to be set to the correct folder and the output type of the plug-in project needs to be set to class library. Furthermore, the plug-in needs to be of the correct namespace in order to be found by Vtrin. Figure 32 shows that once all the aforementioned steps are completed properly, the user can find the plug-in and set his display to it.

In addition to creating the plug-ins, another important common step is that the plug-ins establish a connection to ABB's real-time database (RTDB) and maintain the connection open. This is because the purpose is to be able to display real-time information in the 3D models. Furthermore, the plug-ins have to specify what data is of interest and subscribe to changes in that data. In this manner, every time when a value of a variable of interest changes, the plug-in is notified and takes the appropriate actions to change the visualization of the model.

An important decision that had to be made was how the 3D model and the data relate to each other. In other words, how does a data variable associate with a specific part of the 3D model. A solution to this problem was to create a mapping between the parts of interest in the 3D model and sensor data in the database. This can be achieved by editing the provided 3D models in order to add specific identifiers to the parts of interest, such as IDs or names. The associating mappings can then be either hard-coded into the program or for example, the mappings could be read from a text file which is editable by the user. The latter option is much more flexible and thus, the better solution.

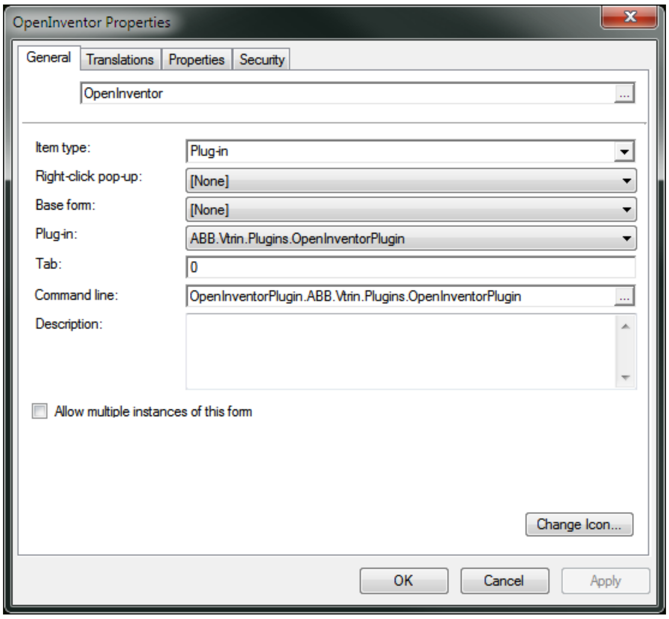


Figure 32: Setting a display as a plug-in in Vtrin.

4.1.3 Open Inventor

Using the Open Inventor tool various interaction techniques were implemented, in accordance with the techniques described in Section 2.4.6, in order to enhance the data visualization experience in the 3D model. The most important of all being the basic manipulations of objects in three dimensional space, such as zoom, pan and rotate. Additionally, selection was implemented to allow the user to mark a part of the model, as well as tooltips (a hovering query), which allow the user to obtain extra information of a part of the model. Furthermore, a change in the background color of the 3D model was implemented which changed in real-time in accordance with the values of test variables coming from the real-time database (darker background color was associated with higher values).

The background color changes were implemented instead of the initially planned color changes for the parts of the 3D model. The reason for implementing a back-up plan instead was due to the very late arrival of the 3D models from the customer, thus leaving no time for editing the 3D models, as described in Section 4.1.2, to create a proper mapping of data.

Figure 33 shows a customer's 3D model of a robot loaded in the Open Inventor plug-in which displays test data coming from the real-time database in a tooltip.

4.1.4 HOOPS Visualize

Using HOOPS Visualize, the same functionalities and user interactions were implemented as with Open Inventor. The used color changes for the background were slightly different, as they had a vertical gradient. Figure 34 shows the result.

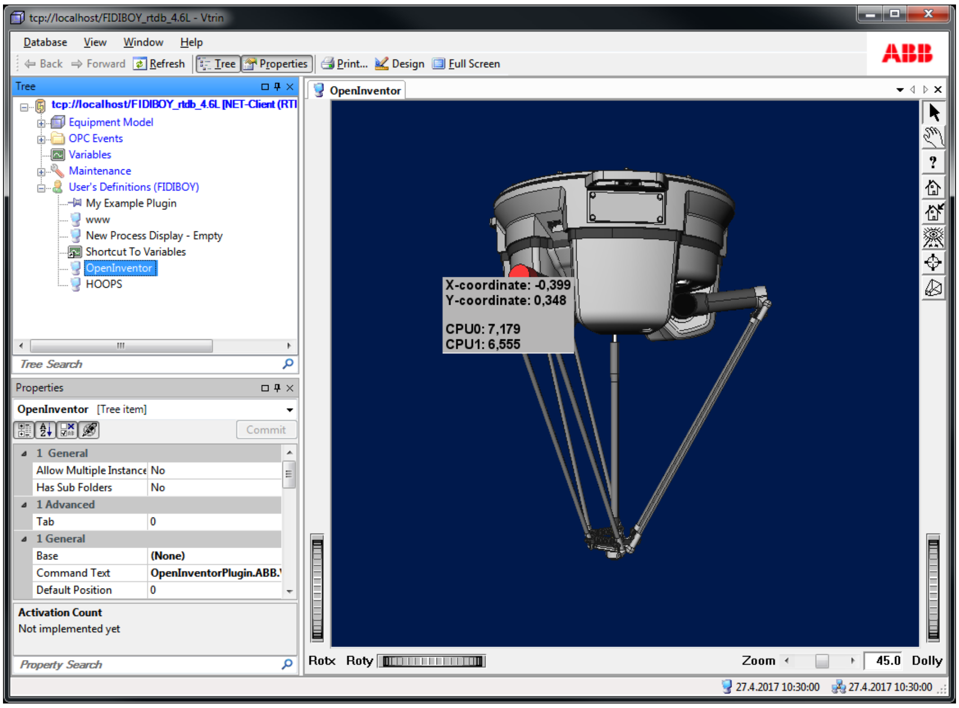


Figure 33: Open Inventor plug-in displaying a 3D model of a robot and real-time test data from a database.

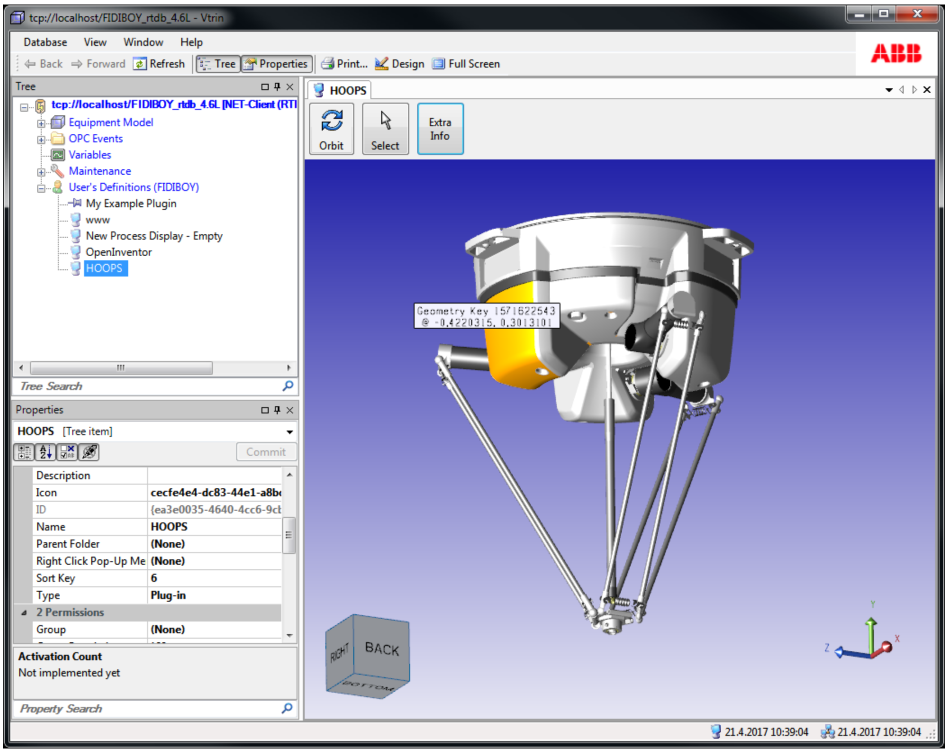


Figure 34: HOOPS Visualize plug-in displaying a 3D model of a robot and real-time test data from a database.

4.2 Case example: Node.js and MiaServer

This section describes the integration process of the 3D tools onto a web framework. The framework has a lightweight node.js server at its base that takes care of the routing and authentication. Additionally, another application called View and, more specifically, a service used by it, called MiaServer, is used for establishing a secure connection to ABB's real-time database.

The integrated 3D visual representations onto the aforementioned web-based framework, which are shown in this section, present the concept deployed on a localhost. The implementation methods differ slightly for the two 3D visualization tools, due to the differences in the tools' architectures, however, both were made to work with the aforementioned node.js server.

4.2.1 Open Inventor

Figure 35 shows a basic 3D visualization in a web browser using the Open Inventor RemoteViz library. The options displayed to the left of the image can be used to change different parameters related to the visualization of the model, such as the maximum frames per second (FPS) and the bandwidth, which affect the compression qualities for still and interactive images send between the server and the client (web browser). The user can perform all basic interactions with the model (zoom, pan and rotate), in addition to which also selection was implemented. A change in the background color was implemented in real-time according to changes in the values of test variables coming from the real-time database. A color with a vertical gradient was used, similarly to the implementation with HOOPS Visualize displayed in Figure 34. Upon user interaction, events are triggered that send requests to the server to perform the needed rendering, which then sends back the resulting image to the client.

4.2.2 HOOPS Communicator

Figure 36 shows the pre-built web viewer of HOOPS Communicator with the loaded customer model. The web viewer provides the basic 3D model manipulations (select, zoom, pan and rotate), as well as more advanced operators — dissect using cutting planes, hidden lines view and exploded view. Changes to the background color were not implemented in this solution due to time constraints.

The solution with HOOPS Communicator allows the 3D rendering to be performed either on the server side or on the client side.

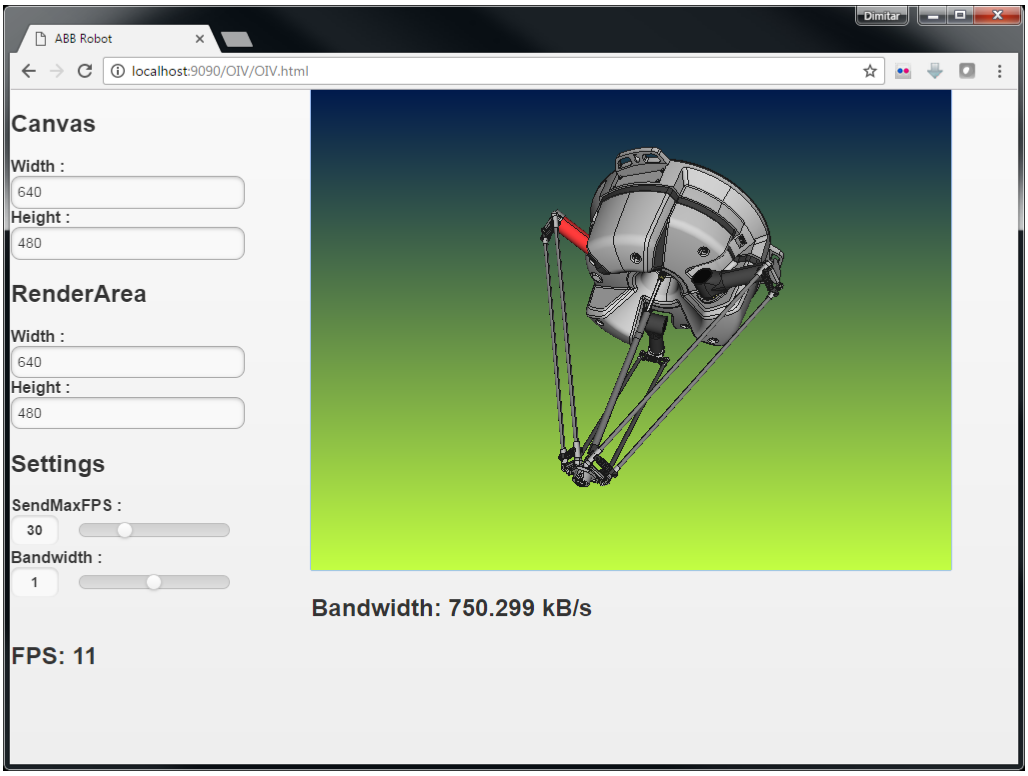


Figure 35: Interacting with a 3D model in a web browser using Open Inventor's RemoteViz.

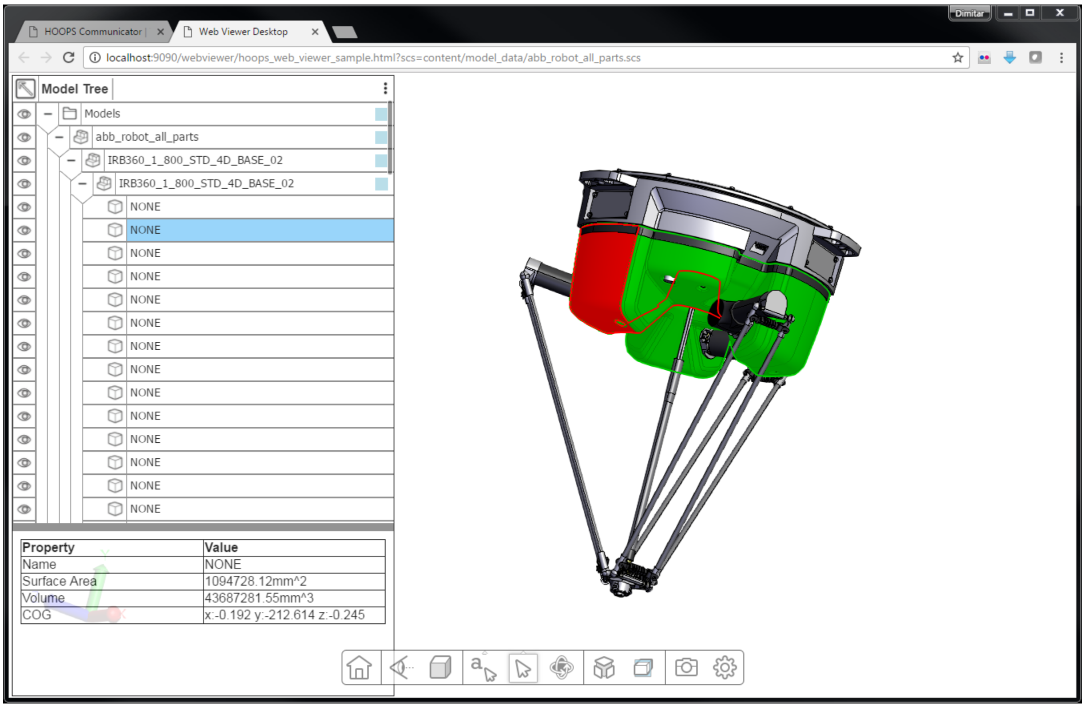


Figure 36: Interacting with a 3D model in a web browser using HOOPS Communicator.

5 Conclusion and Discussion

As a result of this Master's thesis and an answer to the research question "Is it feasible to integrate a 3D visualization component into ABB's process information management systems for more efficient process data visualization that can be commercially utilized?" a proof of concept was developed using a customer's 3D model. This was achieved by integrating two 3D visualization components — Open Inventor by FEI and HOOPS by Tech Soft 3D — into ABB's process information management systems. An implementation methodology was developed and applied for choosing these two 3D visualization toolkits and for evaluating them, in order to guide the choice of the best toolkit to be used for further development of the concept.

For the purpose of meeting the set goals, the Master's thesis was divided into two main parts: literature review and implementation. The extensive literature review of the Master's thesis provided the basis for the thesis. An important survey was conducted on the current situation in manufacturing plants in terms of data collection and visualization in Section 2.2. This was then overshadowed by the immense possibilities of the Industrial Internet of Things and the crucial role it will play in shaping manufacturing industries in the future, as described in detail in Section 2.3. Section 2.4 then moved on to discuss the core principles of process data visualization and the importance of understanding human visual perception when designing intuitive and informative visual representations. It presented some impacts that the IIoT will have on process data visualization and emphasized the importance of interactive techniques in solving these problems.

The implementation part of the Master's thesis was covered in Sections 3 and 4. Section 3 described the developed implementation methodology and its execution. Section 4 discussed the integration process itself of the two selected 3D visualization components into ABB's PIMS solutions and presented the results of the created proof of concept with a customer's 3D model. The tools were specifically chosen by their ability to support the development of 3D visual representations for use in web environments, which is crucial for creating *Industrial Internet of Things* solutions. Section 4 was divided into two parts in order to cover the integration into ABB's existing Vtrin desktop software and to demonstrate the possibility of integration into the new web framework which has node.js at its core.

There were a number of obstacles met during the Master's thesis that had to be solved. The first major obstacle emerged when it became apparent that using SAP 3D Visual Enterprise for the 3D visualization, as initially planned, will not work due to licensing problems. As a result, other available options on the market that are suitable for the productization and that offer technical support had to be researched quickly but extensively.

The second major obstacle arose from the trouble of finding a partner amongst ABB's customers that could supply the required 3D models and associated data for developing the proof of concept. This was partially unexpected and the requested material was obtained towards the very end of the Master's thesis, though the process of contacting customers and requesting the necessary material was initiated at a very early stage. As a result, a lot of work that depended on knowing the type and format of the 3D models could not be done in advance, and was therefore left undone. One such consequence that was left unimplemented was the mapping of variable data, coming from the real-time database, to different parts of the 3D model. Connection to the real-time database and to data, however, was established and demonstrated with changes in the background color of the model instead.

The Master's thesis yielded a number of important discoveries. First of all, from the literature review on the topic "The Industrial Internet of Things" it became apparent that the IIoT is an emerging concept with huge opportunities for manufacturing industries. At the core of these opportunities lies the ability to maximize the usage of data for decision making. This results in largely improved efficiencies by reducing costs, waste and pollution, and increasing flexibility, robustness and reliability, to name a few. Predictive maintenance was identified as one of the first, most direct and most important applications of the IIoT in the short-run and autonomous business processes was determined to be one of the longer-term applications of the IIoT.

Despite these huge opportunities, it was discovered that manufacturing companies are experiencing difficulties in aligning their business models with the IIoT vision and thus, the IIoT adoption rate being rather slow. This discovery from literature was also verified by the visit in a manufacturing facility, presented in Section 2.2, as well as from the pilot cases discussed in Section 3.3. The major reasons for the slow adoption rate were identified to be the currently low maturity of the market, the potential security and privacy risks in adopting the IIoT, and the overconfidence of CEOs in being able to quickly transform when the time is right.

The discoveries made from the second part of the literature review on the topic "Process Data Visualization" were the importance of understanding human visual perception when designing visual representations, the impacts of the IIoT on process data visualization, as well as the role of interactive techniques and the use of 3D visualization of process data in solving the new problems. More specifically, combining various interactive techniques with pre-attentive visual properties and 3D visualization of process data can significantly improve the effectiveness of visual representations in displaying the immense amounts of gathered data emerging from the IIoT.

Various discoveries were made from the applied implementation methodology discussed in Section 3. The evaluation of the two selected tools exposed their similarities and differences, as well as their strengths and weaknesses. From the evaluation of the market maturity it became apparent that the current state of technology of 3D process data visualization in the manufacturing industry is at an early stage of development, with a strong business case to follow in the near future. An important remark was also made that many companies in the manufacturing industry do not currently possess 3D models of their facilities and therefore, ABB might have to create the 3D models as a part of the solution package. Finally, the market research on available 3D visualization tools in Section 4 revealed that integrating a 3D component into ABB's PIMS solutions is technically feasible and demonstrated the results.

Overall the conclusion of this Master's thesis is that both 3D process data visualization and the IIoT are emerging technologies with huge opportunities to companies in the manufacturing industry. Both technologies are at an early stage of development and exhibit high adoption rates in the near future. The markets are in the process of aligning themselves in order to meet customers' needs and customers are in the process of understanding the new opportunities presented to them by these technologies and slowly adopting them. The commercial feasibility of the technologies was, nevertheless, demonstrated by the developed proof of concept in which a 3D visualization component was integrated into ABB's PIMS solutions and a customer 3D model was visualized with test data.

5.1 Vision and future improvements

The developed proof of concept (PoC) was intended to be only the starting point, showing some very basic functionalities applied on a customer's model and test data. The loaded 3D model in itself was very simple as it was a model of only a single machine. The purpose of the PoC was to provide a base on top of which new functionalities and use cases could be developed in the future. The long-term vision of the concept is to have 3D models of an entire manufacturing site along with all its production equipment. The interaction with the models would be such as to adopt the idea of "overview first, zoom and filter, then details on demand", presented in Section 2.4.6. Therefore, the 3D models are to be broken down into a number of different abstract hierarchical levels, each one of them showing different kinds of information to different users, depending on their needs. At the highest hierarchical level only a bird's-eye view of the entire manufacturing site, consisting of different sectors, would be shown. A zoom-in functionality would allow users to seamlessly navigate between hierarchical levels and would display information relevant to them.

In order to provide a better understanding of the idea, this paragraph presents an example of a single factory building with two hierarchical levels: outside the building and inside the building. At the highest hierarchical level, only the building's outside walls are seen. Zooming-in on a part of the building would have a similar effect to physically entering that part of the building. Therefore, the outside walls would be seamlessly filtered out and the user would be presented with a more detailed view of what is inside the building, such as the various pieces of equipment. Zooming out would have the opposite effect of decreasing the level of details and providing more general information to the user.

A number of possible use cases of the concept were discussed during a consulting session with a company called Linja, which is one of the leading user experience (UX) design companies for industrial applications in Finland. Some of the most interesting ideas that were born during the session are listed below:

- Things to display in the 3D model:
  - alarms
  - location-relevant information and messages
  - materials flow
  - people's locations, events and communications

- Possible use-cases:
  - playback functionality for analyzing past events and providing context to situations
  - finding cause-effect relations
  - determining bottlenecks in processes
  - preventive maintenance

Some of the ideas listed above are worth expanding a bit more. Firstly, there is a significant hidden value that can be extracted from displaying information related to people in the 3D models. For example, some of this information may be the role of individuals in the manufacturing process; the team they belong to; their whereabouts in the facility; as well as the communication and cooperation between individuals and teams, to name a few. Being able to see this type of information would increase efficiency via better coordination.

Secondly, a playback functionality would be very valuable for manufacturing where there are several shifts of workers. Currently, it is common that workers coming for their shift have very little or no idea of what has happened in the facility after their previous shift. With the help of playback, workers could go through a virtual morning round of what has occurred while they were gone, which would give them context to situations that might occur during their shift and help them make the right decisions.

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